Estimation of Towing Forces on Oil Spill Containment Booms

prepared by

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Acknowledgments

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1. Introduction

Effective use of skimmers or *in situ* burning for an oil spill generally requires that the spill first be contained using booms. Typically, a containment boom would be towed in a "U" configuration or held stationary against a current in order to contain and thicken oil for recovery or burning. In either case, it is important to know the likely forces imposed on a boom so that appropriately sized tow vessels and towing gear are specified for the operation, and more important, so that boom with sufficient tensile strength is selected. Guidance for selecting appropriate tensile strength is provided in *U.S. Coast Guard 33 CFR Part 155, Vessel Response Plans Final Rule* (USCG 1996), and in *ASTM F1523: Selection of booms in accordance with water body classifications* (American Society of Testing and Materials 1996).

Presently, boom towing forces are estimated using several well-known formulae such as those published in the *World catalog of oil spill response products* (Schulze 1995), *Exxon oil spill field manuals* (Exxon 1982), and *International Tanker Owner's Pollution Federation (ITOPF) field manuals* (ITOPF 1986). These formulae estimate the theoretical loads on a boom based on its dimensions, water current or tow speed, wave height, and wind, and include constants to account for boom profile and gap ratio. Recent field testing carried out for the Marine Spills Response Corporation (MSRC) and the U.S. Coast Guard (USCG) (Nordvik et al. 1995a) has shown that these formulae may severely underestimate drag forces. As a result, commonly accepted values for the minimum required tensile forces in a boom may be well below the actual required values.

A series of tests was carried out at the Ohmsett test facility to measure the towing forces on a number of booms using a range of gap ratios, wave conditions, and tow speeds. The data from these experiments was used to develop a simple relationship to predict the tow force and required tensile strength for the various boom and tow parameters. A comparison was also made between the tow forces as measured in the Ohmsett test tank against those measured in the MSRC / USCG field testing.

2. Objectives

The objective of the study was to determine the loads developed on a containment boom when towed in a typical operational configuration. The work was conducted in four phases:

- a test protocol was prepared and circulated for comment among the project participants;
- equipment for testing was identified and assembled at Ohmsett;
- the tow tests were carried out at Ohmsett in July 1998;
- the results were analyzed and the following report prepared to document the study; and,
- the results were presented to the ASTM F20 Committee and at the Arctic and Marine Oilspill Program (AMOP) Technical Seminar 1999.

3. Previous Work

The first phase of the work was a brief review of recent boom testing that included the determination of towing forces. The goal was to establish the theoretical validity of existing formulae given modification to the constants used for boom shape and gap ratio.

3.1 Existing Formulae for Estimating Tow Forces

The formulae currently used for predicting tow loads on containment boom include the following.

The Schulze formula is known as such as it is published in the *World Catalog of oil spill response products* (Schulze 1995). It was originally published in an Exxon spill manual (Exxon 1982), and is based on a theoretical consideration of the wind and current forces acting on a boom. The formula is as follows:

$$T_a = 0.5\ L\ \tau\ C_d\ \rho_a\ f\ V_a^2$$
$$T_w = 0.5\ L\ \tau\ C_d\ \rho_w\ d\ (V_w + 0.5\ \sqrt{H_s})^2$$
$$D = 2\ (T_a + T_w)$$

where:
- D = total drag force, lb_f
- T_a = tension due to wind, lb_f
- T_w = tension due to waves and current, lb_f
- V_a = wind speed, ft/s
- V_w = current/tow speed, ft/s
- ρ_a = density of air (0.00238 slugs/ft^3)
- ρ_w = density of water (1.98 slugs/ft^3)
- L = length of boom, ft
- τ = tension parameter, dimensionless
- C_d = drag coefficient [assumed to be 1.5], dimensionless
- f = boom freeboard, ft
- d = boom draft, ft
- H_s = significant wave height, ft

It is interesting to compare the effects of wind and water currents on the total load imposed on a boom. For example, using this formula, and assuming that the freeboard dimension is half the draft (which is typical of containment boom), and assuming a 20 knot wind and 1 knot water current

(which are typical containment limits), the load produced by the wind is only 25% of that produced by the current. For that reason the effect of wind is often ignored when estimating forces on a boom.

The tension parameter, "τ", is a function of the gap ratio, and must be read off a graph or from a table (see Figure 1, with selected values for "τ" given in Table 1). This, coupled with the large number of coefficients, can make using the Schulze calculation cumbersome.

Table 1: Tension parameter (τ) for selected gap ratios

Gap Ratio	Tension parameter (τ), dimensionless
0.2	0.025
0.3	0.045
0.4	0.075
0.5	0.115

A similar formula for estimating the expected tow loads on booms is used by ITOPF in their field manuals (ITOPF 1986). While similar to the Exxon equation it is much simpler, using only a constant, the projected area of the boom, and the wind or current velocity as inputs. Note that the ITOPF formula estimates a total force on the boom, in kilograms-force. (It is assumed that this is simply a conversion from units of pounds-force.) As with the Schulze formula, the estimated force due to wind is much less than that due to currents; using the 20 knot wind and 1 knot water current as in the previous example results in a wind induced force that is only 12.5% of the current induced force.

$$F_w = 26\ A_w\ (V_w / 40)^2$$
$$F_c = 26\ A_c\ V_c^2$$

where: F_w = force on a boom due to wind, kg
A_w = freeboard area, m^2
V_w = wind velocity, knots
F_c = force on a boom due to waves and current, kg
A_c = submerged area, m^2
V_c = current/tow velocity, knots

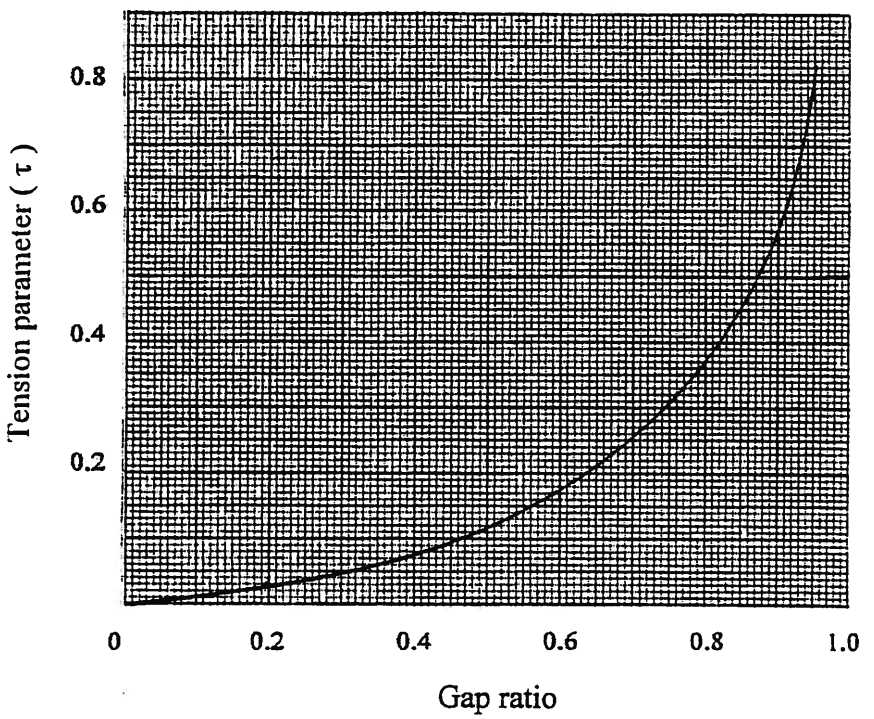


Figure 1: Tension parameter (τ) vs. gap ratio

3.2 MSRC / USCG Testing of Containment Booms

The impetus for the work reported here was a recent field study (Nordvik et al. 1995a) in which tow forces and other boom performance parameters were measured for a number of offshore containment booms. The objective of the work was to collect quantitative data on containment boom performance including tow forces, skirt draft, and boom freeboard as a function of tow speed. Four booms were tested: the 3M Fire boom, the Norlense Barrier boom, the USCG / Oil Stop boom, and the U.S. Navy USS-42 boom.

The measured tow forces were compared with those predicted by the Schulze and ITOPF formulae and it was found that the predictions significantly underestimated the towing loads experienced in the field. In general, for three of the four booms the tow loads predicted by both the Schulze formula and the ITOPF formula were as little as 25 to 50% of the mean loads measured in the at-sea testing. With only one boom - the 3M Fireboom - did the formulae produce an estimate that was similar to that measured in the field tests.

The authors suggested that there were two main reasons for the discrepancy between measured and predicted tow forces: first, that the formulae failed to account for variation in speed between two tow vessels, as would commonly occur in a towing operation at sea; and second, that the formulae failed to account for variation in the gap distance between the two tow vessels, again a problem that would be typical of an actual containment operation. The authors concluded that additional safety factors would have to be applied to any prediction formula to deal with these dynamic effects that would typically be experienced at sea.

Although the predicted forces were much lower than the measured tow forces, the authors did note that the shapes of the force vs. tow speed curves were similar, indicating that a good correlation should be possible with this type of equation using different constants.

4. Test Methodology

4.1 Test Facility and Equipment

The tow tests were carried out at the Ohmsett, the National Oil Spill Response Test Facility test tank in Leonardo, NJ. Performing the tow tests in the Ohmsett tank allowed the use of full-scale containment boom and very good control and measurement over the key parameters of tow speed, gap distance (and hence gap ratio), and tow forces.

The Ohmsett test tank is 667 feet long by 65 feet wide by 8 feet deep. (Figure 2 shows the layout of the tank, the key equipment, and a boom in position for a tow test.) A towing bridge that spans the tank is capable of speeds of up to 6.5 knots. A wave generator at one end of the tank produces waves, and at the opposite end an artificial beach can be raised to absorb wave energy (resulting in a regular wave) or lowered to produce an irregular wave similar to a harbor chop. Different wave heights and lengths can be created by adjusting the stroke and frequency of the paddle. Additional information on Ohmsett is available on the internet at http://www.ohmsett.com.

A load cell was mounted on each of the tow points on the towing bridge. The load cells used had a capacity of 2000 lb_f, with a stated accuracy of ±10 lb_f. (Specifications for the load cells are provided in Appendix A.) The load cells were calibrated prior to the tests and checked afterwards to confirm their accuracy. Data from the load cells, as well as data on wave height and tow speed, were recorded by a computer every 0.1 seconds. Visual observations by test personnel as well as video footage were collected during the test runs to document the behavior of the boom, including submergence, planing, wave conformance, and splashover.

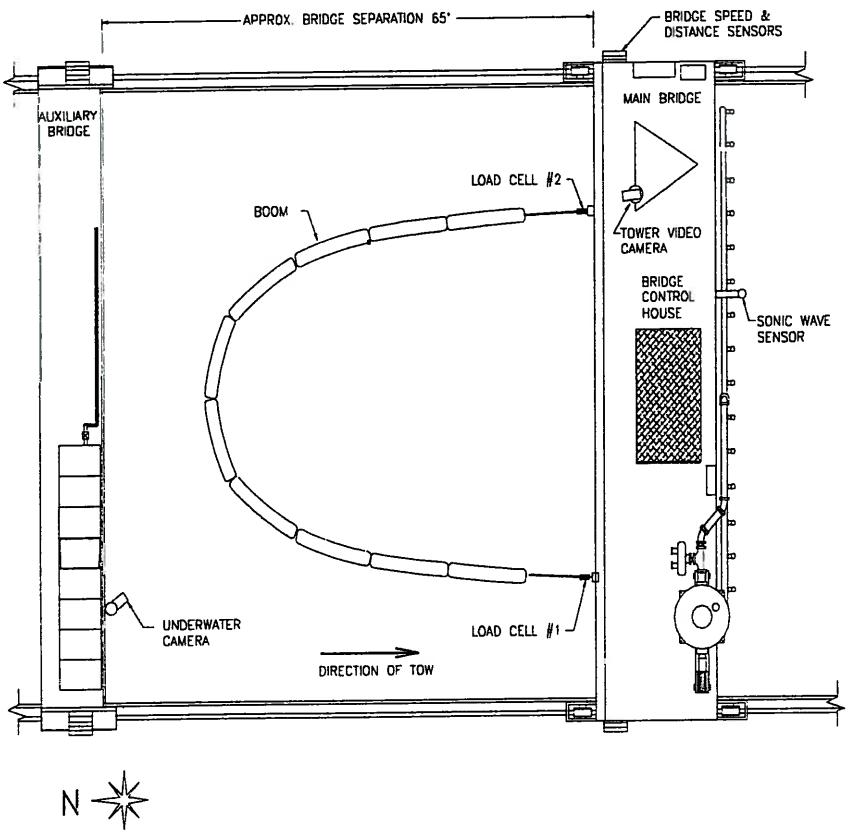


Figure 2: Layout of Ohmsett tank with boom in position for towing

4.2 Containment Booms Tested

In selecting booms for the tests, the goal was to cover a range of commonly-used types and sizes of containment boom. The range of boom types was to include both fence- and curtain-type booms; boom drafts ranging from 12 to 40 inches; and buoyancy-to-weight ratios ranging from 5:1 to 20:1.

Based on these criteria, six containment booms were selected for testing. The key properties for each of these booms are summarized in Table 2. The two sizes of Sanivan curtain-type boom and the two sizes of Flexy fence-type boom are used extensively for containment in nearshore and protected waters. These products use permanent foam floatation, and steel chain as a ballast and tension member. The Ro-boom 2000, the USCG Oil Stop, and the U.S. Navy USS-42 are larger, more rugged booms suited to use in offshore conditions. Each of these booms use individual floatation chambers filled with pressurized air to provide buoyancy, and chain along their bottom edge for ballast and tensile strength. For each boom, an appropriate number of sections was obtained to allow testing of boom lengths of approximately 100 to 150 feet with gap ratios of 0.2 to 0.5.

Table 2: Summary of containment booms tested

Boom	Type	Height, in. (cm)	Draft, in. (cm)	B:W Ratio	Section Length, ft (m)
Sanivan	curtain	18 (46)	11 (28)	5:1	50 (15.2)
Flexy	fence	18 (46)	11 (28)	3:1	50 (15.2)
Sanivan	curtain	24 (61)	13.5 (34)	14:1	50 (15.2)
Flexy	fence	36 (91)	24 (61)	5:1	50 (15.2)
Ro-boom 2000	curtain	67 (170)	43 (110)	20:1	98 (30)
USCG Oil Stop	curtain	47 (119)	30 (76)	20:1	55 (17)
USN USS-42	curtain	52 (132)	36 (91)	8:1	82 (25)

4.2 Test Variables

The test matrix included four independent test variables: tow speed, wave condition, boom length, and gap ratio. In general, the booms were towed at four speeds (0.5 to 2.0 knots) under three wave conditions (calm, regular, harbor chop, conditions listed in Table 3) and with four boom configurations (gap ratios from 0.2 to 0.5). This led to each boom undergoing up to 48 test runs lasting approximately one minute each. In all, 358 test runs were carried out over a period of 12 days from June 24 to July 10, 1998.

Table 3: Summary of wave conditions used

Wave type	Significant wave height, in. (cm)	Average Period, s
calm	0	–
regular wave	7.3 (19)	2.1
harbor chop	12.3 (31)	1.7

Within each one-minute test run, ten seconds were allotted at the beginning of the tow to allow the booms to achieve a steady state configuration. The final 50 seconds of data (a total of 500 readings) were extracted from the computer record and analyzed.

With one load cell on each of the two tow points, the tension acting on the boom at a given point in time was calculated according to:

$$T_{ave} = \frac{1}{2} \left(\text{Load cell}_1 + \text{Load cell}_2 \right)$$

The tension experienced by a boom is not constant, particularly when towed through waves. As the boom follows the crests and troughs of the waves the tension fluctuates, peaking when the apex of the boom catches the front of a wave. Peak and mean tension values were determined, with the peak loads defined as the 95th percentile of the tension readings recorded for each run. Because a boom

must be designed to be able to withstand these peak tensions, the focus of the subsequent analysis was on these 95th percentile tension readings.

Wind speeds through the test program averaged 6.0 knots, with only one daily average exceeding 8 knots (The average wind speed was 10.8 knots during the first day of testing the US Navy boom). At these low wind speeds, the wind load on the boom would be a minor component of the total load on the boom, and was therefore not considered in the analysis (see section 3.1 for a discussion of the relative effect of wind vs. current).

5. Results

The data for each test run was tabulated with the mean and peak tow force vs. the tow speed for a given length of boom, gap ratio, and wave condition. The data were compared with the Schulze and ITOPF formula predictions, and with the MSRC field tests for the USS-42 and USCG Oil Stop booms. The data were then analyzed to produce a correlation between tow speed, boom dimensions, and the resulting tow forces.

5.1 Comparison of Results with Formula Predictions

An example of the tow force data is given in Figures 3 and 4, which also show a comparison of the measured tow force data vs. that predicted by the Schulze and ITOPF formulae. For the tests shown in Figure 3, in calm conditions, the Schulze formula greatly underestimates the actual tow loads in all cases, while the ITOPF formula significantly overestimates the tow loads for three of the four booms shown. For the tests shown in Figure 4, in regular waves, both the Schulze formula and the ITOPF formula greatly underestimate the actual tow loads in all cases.

5.2 Comparison of Results with Field Testing

Two booms from this study were also tested in the 1995 field testing sponsored by MSRC and USCG (Nordvik 1995a). The results from the field tests were compared with the data collected in this study. Data on the field tests is taken from Sloan et al. 1994, and Nordvik et al. 1995b.

Table 4 below summarizes the data from the field tests involving the U.S. Navy USS-42 and the USCG Oil Stop booms (also see Figure 5). The average tow force vs. tow speed is listed for each of those two booms, as is a "scaled-down" tow force that accounts for the decreased length of boom used in the tank tests described in this report. In the case of the USS-42 boom, a gap of 300 feet was used: compared with the 55.5-foot gap used in the tank tests means that the tow force is reduced by a factor of 5.4 (i.e., 300 ÷ 55.5) for a valid comparison. Similarly, the results for the USCG boom

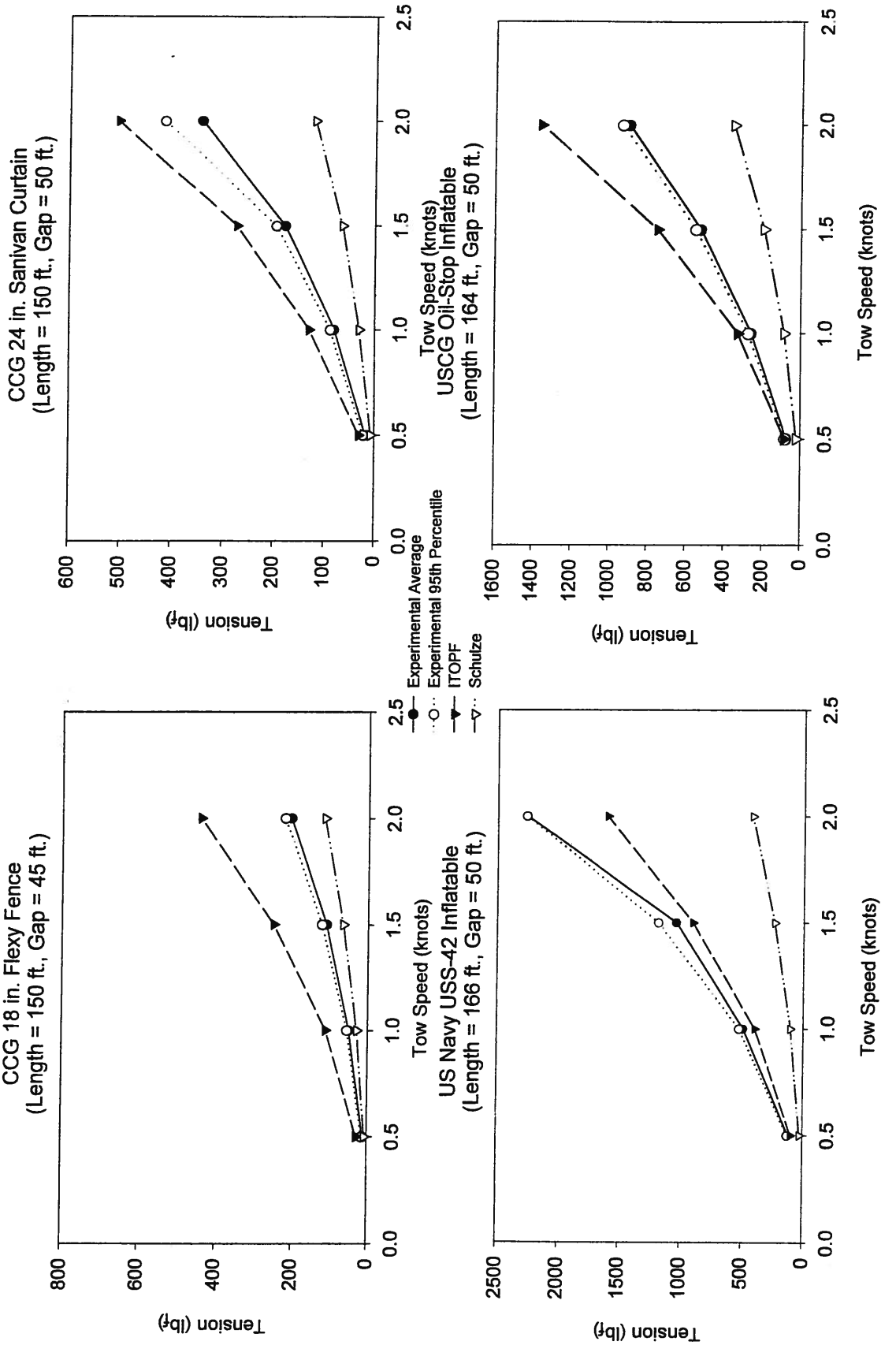


Figure 3: Comparison of Tow Force Data in Calm Conditions with ITOPF and Schulze Equations

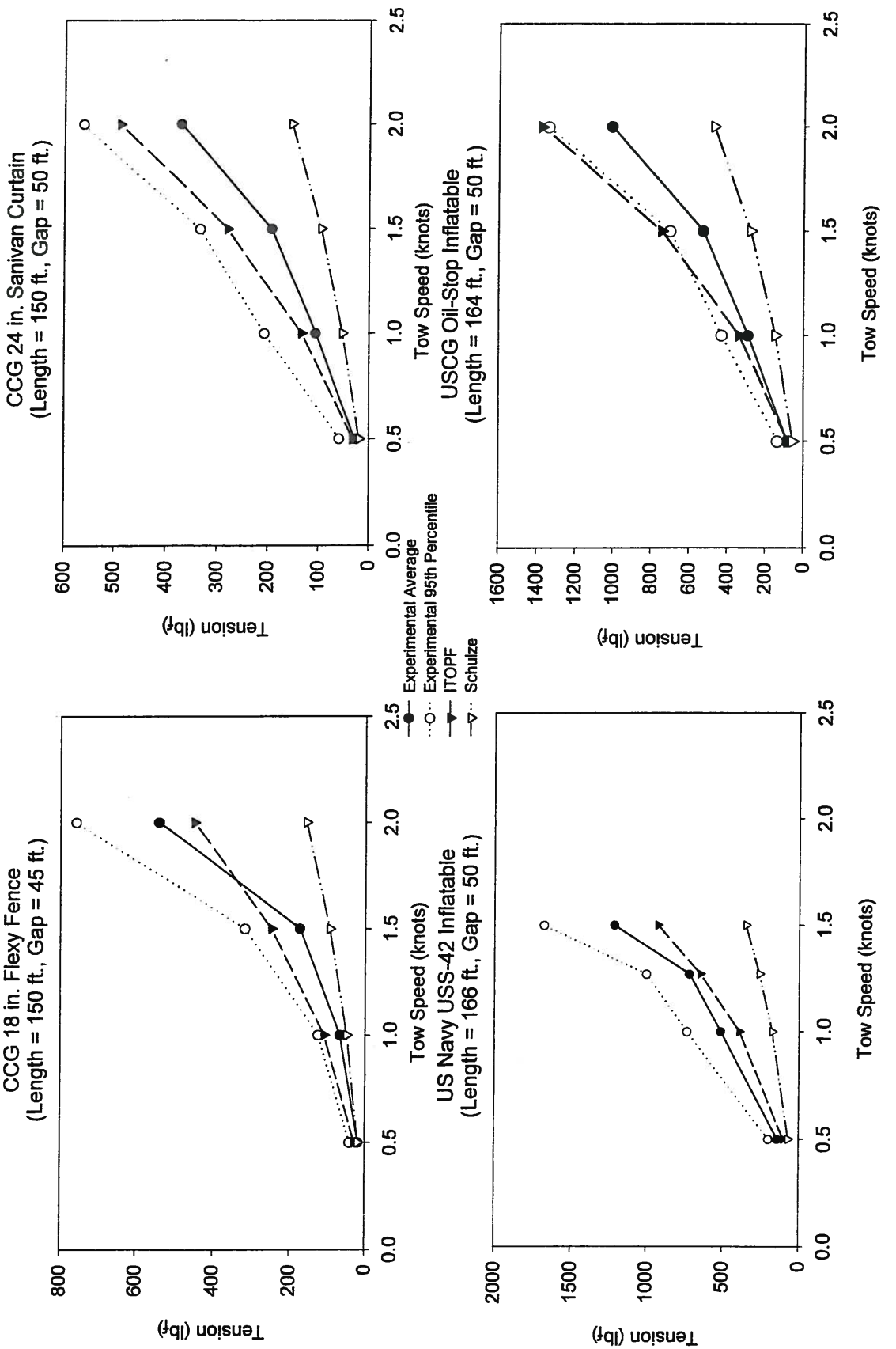
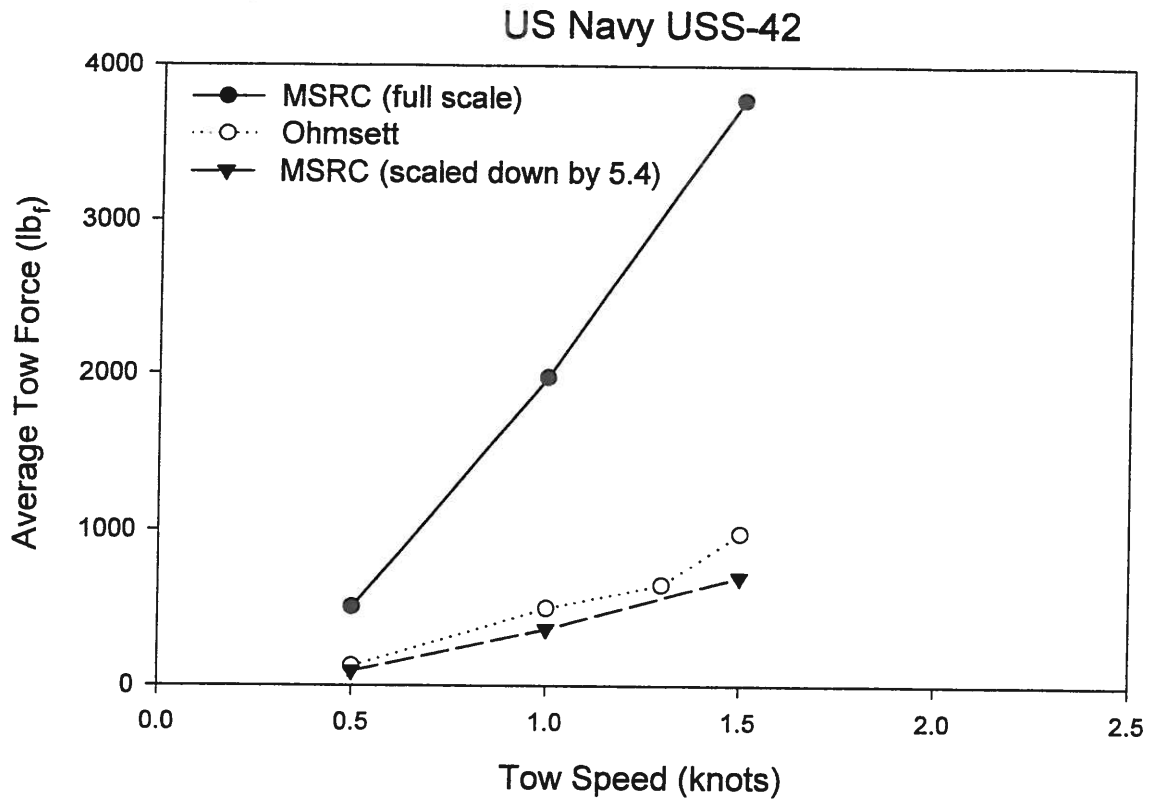


Figure 4: Comparison of Tow Force Data in Harbor Chop with ITOPF and Schulze Equations



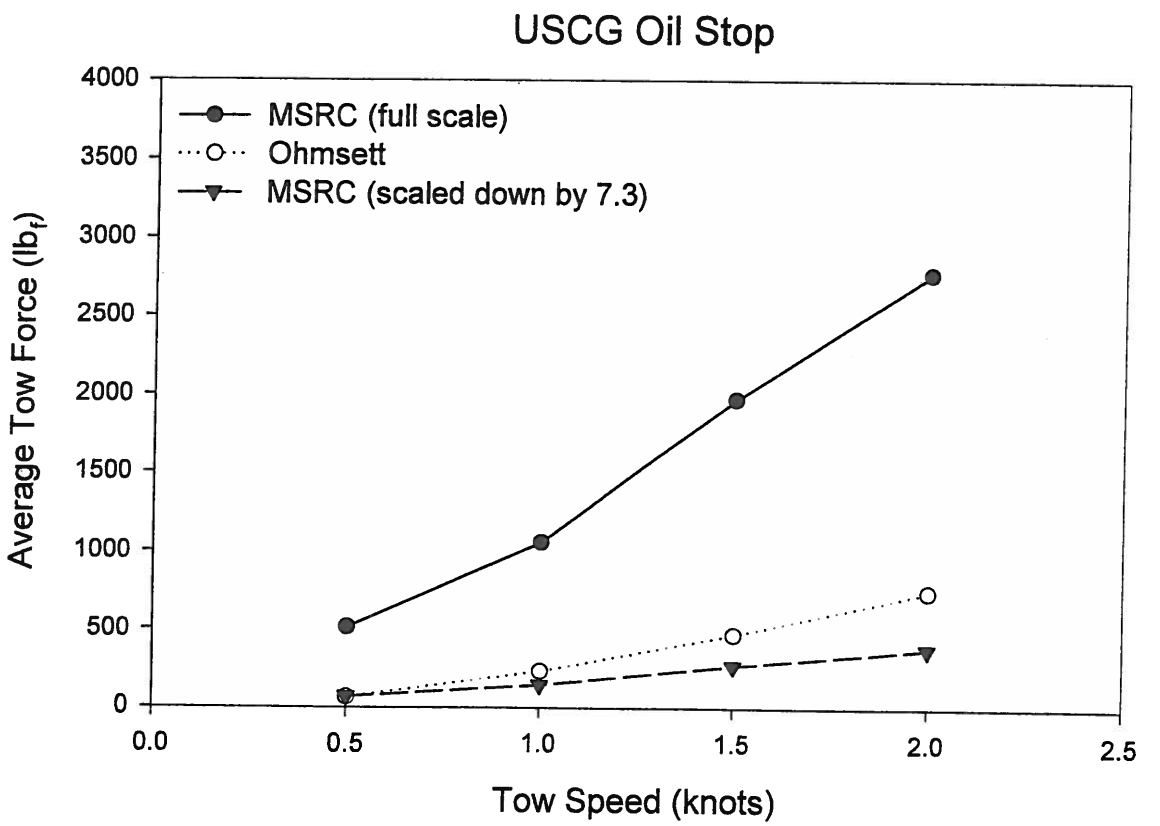


Figure 5: Comparison of MSRC Field Test Data with Test Tank Data

are reduced by a factor of 7.3 to account for the difference between the 300-foot swath width of boom used in the ocean testing and the 41-foot gap used in these tank tests (300 ÷ 41 = 7.3).

Table 4: Comparison of data with MSRC tests

Boom	Tow Speed, knots	Mean Tow Force, lb_f			Difference, %
		Tank Tests	MSRC	MSRC (scaled down)	
USS-42	0.5	127	507	94	-26
	1.0	499	1974	365	-27
	1.3	690	--	--	--
	1.5	978	3779	699	-29
USCG	0.5	66	513	70	+6
	1.0	232	1059	145	-38
	1.5	468	1970	269	-42
	2.0	744	2768	378	-49

For all but one of the comparable test runs, the scaled-down tow forces from the in-ocean testing were consistently less than the forces measured in the test tank, averaging 27% less for the USS-42 boom, and averaging 31% less for the USCG boom. On one hand, the consistent difference between the two of 30% or more indicates that there may be some fundamental difference between the two test protocols. The authors of the MSRC study did note that they had concerns over the lack of control over tow speed and gap width, both of which would affect the tow force but it is unlikely that this would completely explain a 30% difference in measured force. On the other hand, it is encouraging to find that the test tank data and field data are at least roughly comparable and that the difference between the two is at least consistent. While a 30% difference may seem to be larger than one would like, it is certainly within typical safety factors that would be used in selecting containment equipment and towing gear. Noting that a doubling of tow speed would result in a quadrupling of boom tension, a safety factor of 300% or more is not unreasonable.

5.3 Correlation of Results

The data for all the booms was then tabulated for the various tow speeds, gap ratios, and wave conditions. A summary page for each boom is shown in Appendix B, and graphs showing the tow force vs. tow speed for each boom are shown in Appendix C. An attempt was then made to correlate the data against a simple formula that included the tensile force developed in the boom, the projected area of the submerged portion of the boom, and the tow speed:

$$T = 1.4\ K\ A\ V^2$$

where: T = tensile force, lb_f
K = constant, dimensionless
A = projected area of the submerged portion of the boom, ft^2
V = tow speed, knots

(Note the inclusion of a conversion factor of 1.4 $lb_f/(ft^2 \cdot knots^2)$ to maintain consistent units: later, for simplicity, this conversion factor will be included in the constant, K'.)

Correlation was done using a least-squares fit. In general the correlation was very good, with all but a few R-squared values 0.95 or greater. (Correlation coefficients for each of the test runs are shown with the graphs in Appendix C.) The value of the constant K, is listed in Table 5 for the various booms types. It can be seen that the value of K varied from as low as 1.2 to an average of 1.9 for the calm condition, increasing significantly to an average of 3.0 and 3.4 for the regular wave and harbor chop, respectively.

Table 5: Value of constant K, for various booms

Boom	Calm condition	Regular Waves	Harbor Chop
Sanivan 18" curtain	1.2	2.0	2.2
Flexy 18" fence	1.2	3.5	3.9
Sanivan 24" curtain	1.4	2.0	2.5
Flexy 36" fence	2.3	4.1	5.0
USCG Oil Stop	1.4	2.1	2.1
Ro-boom 2000	3.4	4.3	4.7
USN USS-42	2.4	3.2	3.3
maximum	3.4	4.3	5.0
average	1.9	3.0	3.4

In order to simplify the formula, one can combine the conversion factor of 1.4 $lb_f/(ft^2 \cdot knots^2)$ with the constant K, which would produce a constant K' (Table 6), to be used as follows:

$$T = K' A V^2$$

where: T = tensile force, lb_f
K' = constant, $lb_f/(ft^2 \cdot knots^2)$
A = projected area of the submerged portion of the boom, ft^2
V = tow speed, knots

Table 6: Value of constant K', for various booms

Boom	Calm condition	Regular Waves	Harbor Chop
Sanivan 18" curtain	1.7	2.8	3.1
Flexy 18" fence	1.7	4.9	5.5
Sanivan 24" curtain	2.0	2.8	3.5
Flexy 36" fence	3.2	5.7	7.0
USCG Oil Stop	2.0	2.9	2.9
Ro-boom 2000	4.8	6.0	6.6
USN USS-42	3.4	4.5	4.6
maximum	4.8	6.0	7.0
average	2.7	4.2	4.7

This can be compared with the ITOPF formula, described previously, which predicts total load on a boom for a given submerged boom profile and tow speed. Using a range of the above values for K' of 3.4 to 4.7, and correcting for unit conversions and the fact that the ITOPF formula is for total load (i.e., twice the tensile force) leads to a constant for the ITOPF formula of 26 to 46, as compared with the value of 26 that is assumed.

5.4 Grouping of Results by Boom Size and Type

Among the smaller booms, there is a considerable difference between the fence-type and curtain-type booms: the values of the constant K' averages 2.5 under calm conditions and 6.3 under harbor chop for the fence booms, as compared with 1.9 and 3.3 for the curtain booms. This is probably a reflection of the less streamlined shape of the fence-type booms, coupled with their lower buoyancy and concomitant tendency to submerge at tow speeds in excess of 1.5 to 2 knots.

Overall, there is a considerable range in the values of the constant K'. However, there is a trend of increasing value of the constant with boom size. It would be useful to group the results according to boom size, using the size ranges for boom provided by ASTM F1523: *Selection of booms in accordance with water body classifications* (ASTM 1996), as shown in Table 7.

Table 7: Recommended size of boom per water body

Water Body Classification	Wave Height Range*, ft.	Boom height, in.
calm	0 to 1	6 to 24
protected	0 to 3	18 to 42
open water	0 to 6	> 36
* From ASTM F625 *Classifying Water Bodies for Spill Control Systems*		

Grouping the results according to this table, and using the calm water values for the "calm" classification, regular wave values for "protected water", and the harbor chop values for "open water", results in the following values for the constant K' (Table 8).

Table 8: Values of constant K' for booms grouped according to water body classification

Water Body Classification	Average Value of Constant K'
Calm Water (18" booms)	1.7
Protected Water (24" and 36" booms)	4.3
Open Water (47", 52", and 67" booms)	4.7

6. Conclusions

A series of towing tests was carried out at the Ohmsett tow tank to measure the loads imposed on a containment boom while under tow. The tests included a range of boom types and sizes, a range of boom lengths and gap ratios, and a range of wave conditions.

Two of the booms tested in this study had undergone tow testing in a recent field study allowing the comparison of results. The tow forces measured in the in-ocean field testing were found to be approximately 30% less than the forces measured in this study.

Based on the tests in this study, a simple relationship was developed correlating the tensile force developed in a boom vs. the projected area of the submerged portion of the boom and the tow speed:

$$T = K' A V^2$$

where: T = tensile force, lb_f
K' = constant, $lb_f/(ft^2 \cdot knots^2)$
A = projected area of the submerged portion of the boom, ft^2
V = tow speed, knots

The value of the constant, K', varied from a minimum of 1.7, observed under calm conditions, to a maximum of 7.0 observed under the harbor chop condition.

The results were grouped according to water body classifications of calm water, protected water, and open water, with the following results. The value of the constant, K', averaged: 1.7 for calm water booms under calm conditions; 4.3 for protected water booms in regular waves; and 4.7 for open water booms under the harbor chop wave condition.

7. Recommendations

The results of the towing tests described in this study were used to develop a simple relationship correlating the tensile force developed in a boom vs. the projected area of the submerged portion of the boom and the tow speed. The value of the constant used in that relationship is significantly higher than that used in other similar tow load formulae. A range of constants is recommended for use in the formula, depending on the size of the boom and the intended application (i.e., calm, protected, or open water).

ASTM standard F1523, *Selection of booms in accordance with water body classifications*, specifies minimum physical dimensions and other properties for oil spill containment boom. Of interest here is that the minimum tensile strength requirements in F1523 are based on a formula that has been found to significantly underestimate the tow loads and thus the required tensile strength. The results of this study should be used to revise these minimum tensile strength requirements accordingly. A summary of this study will be presented to the ASTM subcommittee on booms for consideration.

Given the variation in the value of the formula constant for different boom types and shapes, it would be desirable to determine the tow loads for a greater range of boom sizes and shapes. Therefore it is recommended that the measurement of tow loads be included in boom test protocols for field or tank testing.

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Appendix A:

Specifications and Calibration Curves of Load Cells

CHC CANADIAN HYDRAULICS CENTRE

14 September 1998

Mr. Steve Potter
Vice-President
S.L. Ross Environmental Research Ltd.
717 Belfast Road, Suite 200
Ottawa, Ontario
K1G 0Z4
Tel: 232-1564

Re: Calibration and rental of two 2000 lb pancake load cells for OHMSETT towing tests

Dear Steve:

Thank you for returning the two Model 1210AJ 2000 lb Interface pancake-type waterproofed load cells in good shape following your boom towing tests at OHMSETT.

On August 4, we checked the calibration of each load cell to make sure they weren't overloaded during your towing tests and to see if they changed. Basically, they checked out very well and the original calibrations we did for you on 18 June 1998 may be applied for your results from OHMSETT. This assumes of course that the 10.00 VDC excitation voltage applied by OHMSETT to each cell was accurate, as was the gain of 200. Communication between our electronics technicians and OHMSETT before your tests confirmed that this would be the case.

Figures 1 and 2 are the 18 June 1998 calibrations for load cell serial numbers 76365A and 32113 respectively. Also attached for your information, are two sheets from Interface Inc. with more information on the characteristics of the load cells.

To calibrate the two waterproofed Interface pancake type load cells, we hung various weights up to about 1800 lbs. A Terascience signal conditioner provided the 10.00 VDC excitation, as well as the 200 gain, and a 50 Hz filter. Output voltage from the strain gauge load cells was then converted by the Neff A/D converter and sampled by a VAX computer. The actual weights applied were measured with a second accurate master load cell that had been previously calibrated by the Structures Laboratory of the NRC Institute for Aerospace Research against known weights.

Ottawa, Canada K1A 0R6
Fax: (613) 952-7679 Internet: http://www.chc.nrc.ca

National Research Council Canada Conseil national de recherches Canada

The accuracy of the two pancake load cells is traceable to calibration of the master load cell. It is estimated that an accuracy of 0.02% of full scale, or +/- 4 pounds, may be expected for the two load cells.

From the straight line fitted to the calibration data, an equation of the form

$$Y = C_o + C_1 .V$$

is given for each load cell, where C_o and C_1 are the intercept and slope respectively, and V is the amplified output voltage. Values are given on each calibration sheet. The top table on each sheet shows the errors between the points and the fitted curve to be very small.

The total cost for rental of the two load cells, their calibration before use by you at OHMSETT, and a complete check of their calibration afterwards, is $3000.00 plus GST as originally estimated on the NRC 32 application form dated 17 June 1998. Trusting this short report meets your requirements, you will be invoiced in the near future.

Yours sincerely

Bruce Pratte, Ph.D., P.Eng.
Director
Canadian Hydraulics Centre
Tel: 993-2417
Fax: 952-7679
E-mail: Bruce.Pratte@nrc.ca

cc: Michel Pronovost, CHC Admin.

Figure 1 **Calibration of Interface Load Cell 76365A for S.L. Ross Environmental Research Ltd.**

18 June 1998

Sensor: Load Cell 1 Model: Interface Inc Serial Number: 76365A

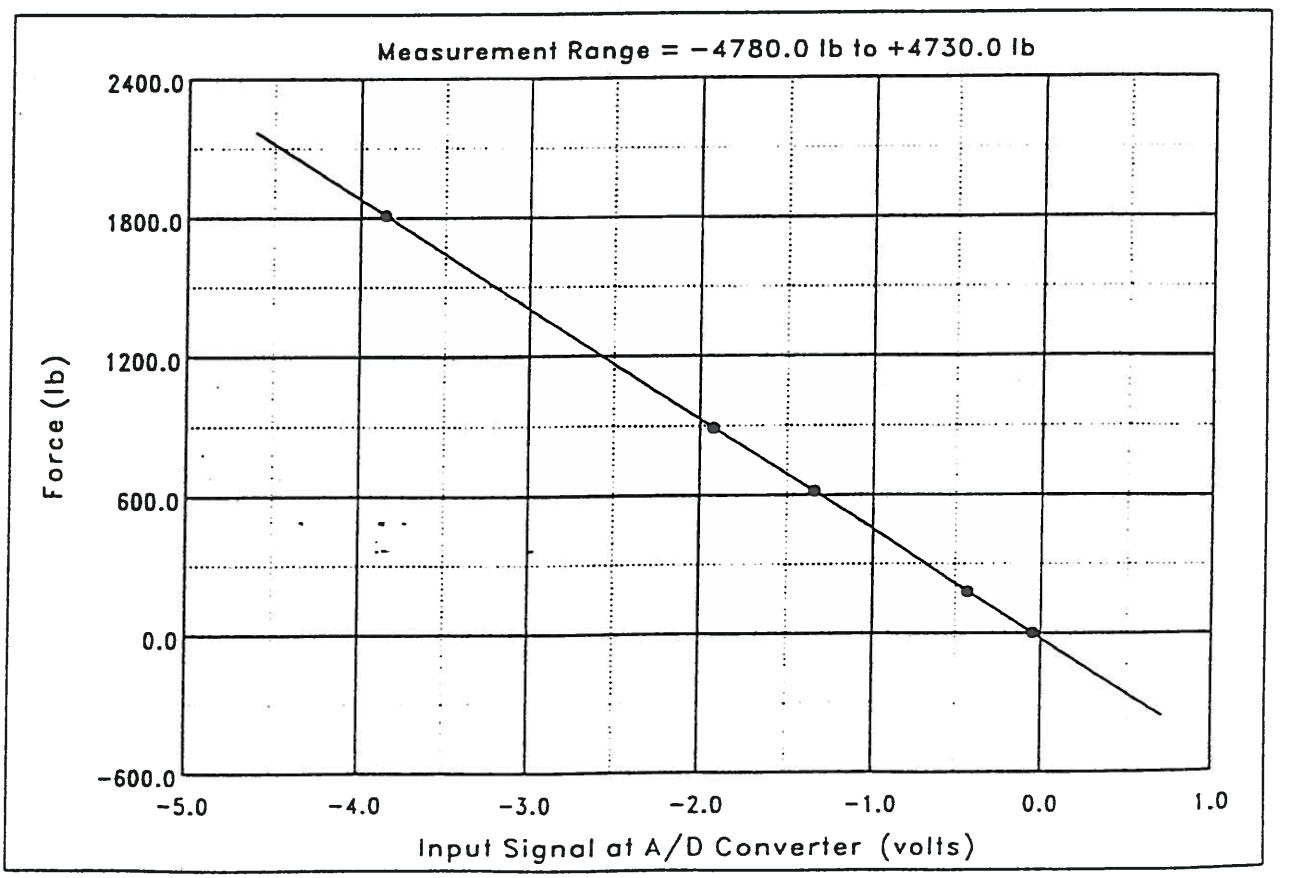
Programmable Gain: 200 Plug-In Gain: 1 Filter Frequency: 50.0 Hz

Data Point No.	Input Signal (volts)	Physical Value (lb)	Fitted Curve Value (lb)	Error (lb)	
1	−0.046	0.2	−1.1	−1.2972	⇐ Maximum Error
2	−0.427	179.3	179.9	0.6126	
3	−1.343	615.3	615.9	0.6172	
4	−1.921	890.1	890.8	0.6689	
5	−3.849	1808.7	1808.1	−0.6016	
Maximum Error = −0.0717 % of Calibration Range.					

Definition of Calibration Curve
Polynomial Degree = 1 (Linear Fit)

$$Y = C_0 + C_1 \cdot V$$

where $Y(t)$ = Force (lb),
$V(t)$ = input signal at A/D converter (volts),
C_0 = −23.1332 lb,
and C_1 = −475.732 lb/volt .



CHC CANADIAN HYDRAULICS CENTRE

Figure 2 **Calibration of Interface Load Cell 32113 for S.L. Ross Environmental Research Ltd.**

18 June 1998

Sensor: Load Cell 2 Model: Interface Inc. Serial Number: 32113

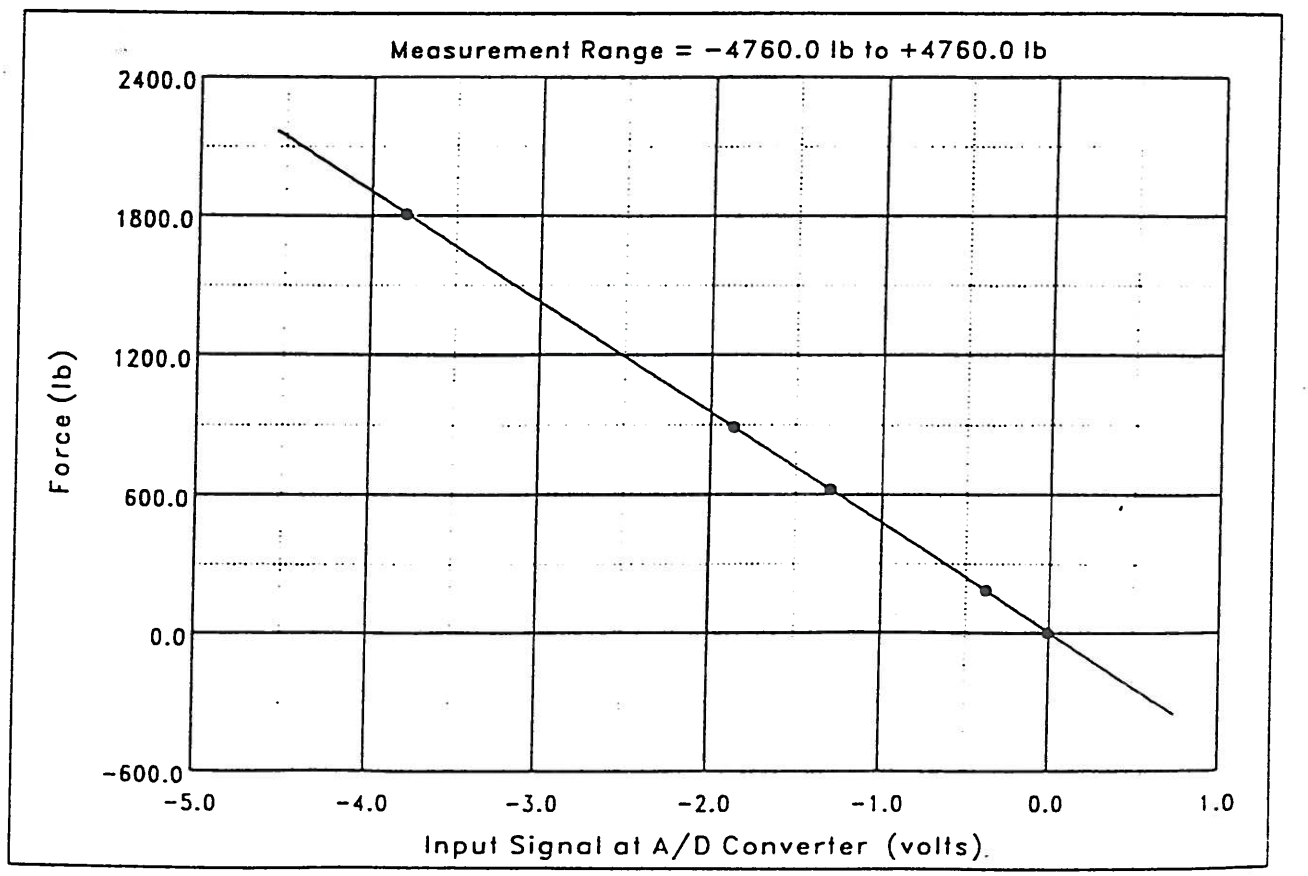
Programmable Gain: 200 Plug-In Gain: 1 Filter Frequency: 50.0 Hz

Data Point No.	Input Signal (volts)	Physical Value (lb)	Fitted Curve Value (lb)	Error (lb)	
1	−0.005	0.2	4.2	3.9513	⇐ Maximum Error
2	−1.298	620.7	619.7	−0.9974	
3	−0.378	184.9	181.9	−3.0770	
4	−1.864	889.8	888.8	−1.0198	
5	−3.798	1808.2	1809.3	1.1428	
Maximum Error = 0.219 % of Calibration Range.					

Definition of Calibration Curve
Polynomial Degree = 1 (Linear Fit)

$$Y = C_0 + C_1 \cdot V$$

where $Y(t)$ = Force (lb),
$V(t)$ = input signal at A/D converter (volts),
C_0 = 1.98977 lb,
and C_1 = −475.894 lb/volt.



CHC CANADIAN HYDRAULICS CENTRE

MODEL : 1210AJ
SERIAL : 76365

CALIBRATED BY : [signature]
DATE : 08-08-94

CALIBRATION CERTIFICATION

BRIDGE : A RANGE : 2000 LBS

INPUT RESISTANCE : 352.7 OHMS

OUTPUT RESISTANCE : 350.5 OHMS

RECOMMENDED EXCITATION : 10 VDC OR VAC

MAXIMUM EXCITATION : 20 VDC OR VAC

COMPENSATED TEMPERATURE RANGE : 15 °F TO 115 °F

TEMPERATURE EFFECT ON ZERO : 0.08 %FS/100°F

ZERO BALANCE : -0.441 %FS

	TENSION	COMPRESSION
NON-LINEARITY	-0.0070 %FS	-0.0070 %FS
HYSTERESIS	-0.0100 %FS	0.0010 %FS
OUTPUT	2.0802 mV/V	-2.0817 mV/V
STATIC ERROR BAND	±.0080 %FS	±.0050 %FS

STATIC ERROR BAND - The band of maximum deviations of the calibration curve from the best fit line through zero including the effect of non-linearity, hysteresis and non-repeatability, expressed as a percentage of rated output.

SHUNT CALIBRATION

60 K OHMS ± 0.01% 1391.161 LBS TENSION

60 K OHMS ± 0.01% 1405.922 LBS COMPRESSION

Shunt calibration resistor connections for tension and compression respectively are (-EXC to -OUT) and (+EXC to -OUT) for 4 wire models; (-SENSE to SHUNTCAL) and (+SENSE to SHUNTCAL) for 7 wire models.

NOTES: _____

_____

INTERFACE, INC.

7401 EAST BUTHERUS DRIVE · SCOTTSDALE, ARIZONA 85260, U.S.A.
TELEPHONE (602)948-5555 · FAX (602)948-1924 · TELEX 825-882

15-53C

Customer WILLER ENG

Sales Order 9425 Model 1216-AF-2K

Purchase Order

CALIBRATION

Bridge*

Range 2,000 lbs.

Date 2/27/96

Serial No. 32113

Input Resistance	350.1	ohms
Output Resistance	350.1	ohms
Recommended Excitation		10 VDC or VAC
Maximum Excitation		20 VDC or VAC
Non-Linearity (terminal) (Above 2 K refer to NOTES)	.005	% FS
Hysterosis (Above 2 K refer to NOTES)	.000	% FS
Compensated Temp. Range	±15 °F to ±115	°F
Thermal Zero Shift	.0003	%FS/°F
Zero Balance	-.52	%FS
Tension Output	—	MV/V
Compression Output	2.031	MV/V

*For multiple bridge load cells.

WIRING

Function	Pin		Pigtail	
	Tens.	Comp.	Tension	Compression
+ Excitation	A	A	Red-Wht/Red	Red-Wht/Red
+ Output	B	C	Green	Wht-Wht/Yel
- Output	C	B	Wht-Wht/Yel	Green
- Excitation	D	D	Blk-Wht/Blk	Blk-Wht/Blk
Shield				

Polarity shown results in positive output

SHUNT CALIBRATION

— ohms

60K ± 0.01% ohms

- Exc. to - Out. — lbs

- Exc. to + Out. 1396.0 lbs.

NOTES:

STATIC ERROR BAND - The band of maximum deviations of the calibration curve from the best fit line through zero including the effect of Non-Linearity, Hysteresis and Non-Repeatability, expressed as a percentage of Rated Output.

± — In Tension

± .004 In Compression

For Universal model load cells, use of a jam nut is recommended in order to reproduce conditions of calibration and to achieve best performance. See Installation Information for jam nut installation instructions.

NOTES:

INTERFACE, INC.
7401 EAST BUTHERUS DRIVE • SCOTTSDALE, ARIZONA 85260
TLX 825-882 TELEPHONE 602-948-5555 USA

Appendix B:

Summary of Recorded Tow Force Values per Boom

CCG 18 in. Curtain Boom - Summary Page

	Section	Length (ft)	Total Height (in.)	Draft (in.)	Free-board (in.)	Buoy. to wt.
Boom Characteristics	1	50.00	18.5	13.5	6	5
	2	50.00				
	3	50.00				

	Length (ft)	Gap (ft)	Gap Ratio	Tow Speed (knots)	Tension Average (lb_f)	Tension Std. Dev. (lb_f)	Tension 95th Perc. (lb_f)	Change in Draft Apex (in.)	Change in Draft Arm (in.)
Calm Runs	150.0	50	0.33	0.5	18.4	3.3	21.3	0.3	0.0
				1.0	74.6	4.7	81.0	0.2	0.0
				1.5	178.7	8.1	194.5	-0.7	-0.2
				2.0	330.4	20.7	372.6	-2.2	-0.4
	150.0	30	0.20	0.5	14.3	3.3	18.8	0.1	0.0
				1.0	57.7	5.1	64.0	0.3	0.3
				1.5	114.5	6.6	126.2	-0.6	0.3
				2.0	198.8	6.4	209.1	-1.3	0.6
	100.0	30	0.30	0.5	15.6	3.2	20.0	0.1	0.4
				1.0	60.5	3.9	66.4	0.0	0.7
				1.5	115.9	13.0	127.5	-0.6	-0.8
				2.0	229.4	7.4	242.1	-1.1	-0.3
	100.0	50	0.50	0.5	22.7	2.8	27.4	0.0	0.1
				1.0	83.5	7.4	94.5	-0.2	0.4
				1.5	195.1	8.0	208.0	-2.0	-1.2
				2.0	398.8	29.7	460.5	-5.2	-1.6
Regular Wave Runs	150.0	50	0.33	0.5	31.0	14.0	57.9		
				1.0	95.3	50.2	189.7		
				1.5	200.7	109.5	387.4		
				2.0	349.2	127.7	554.5		
	150.0	30	0.20	0.5	18.0	10.1	39.5		
				1.0	60.5	32.6	124.9		
				1.5	133.5	81.2	280.0		
				2.0	203.4	90.0	355.6		
	100.0	30	0.30	0.5	21.5	11.7	44.4		
				1.0	62.9	36.1	131.1		
				1.5	128.3	73.5	270.2		
				2.0	234.3	89.9	376.3		
	100.0	50	0.50	0.5	27.5	16.2	55.4		
				1.0	96.3	64.3	215.3		
				1.5	218.0	110.3	397.1		
				2.0	402.5	110.4	572.7		
Harbor Chop Runs	150.0	50	0.33	0.5	27.2	18.5	59.2		
				1.0	93.4	59.9	196.1		
				1.5	205.4	88.9	381.1		
				2.0	383.2	132.9	624.0		
	150.0	30	0.20	0.5	20.5	14.2	46.9		
				1.0	61.0	34.6	125.0		
				1.5	126.1	59.7	243.4		
				2.0	219.5	81.5	367.8		
	100.0	30	0.30	0.5	20.7	17.9	56.7		
				1.0	69.6	44.5	138.4		
				1.5	136.1	68.2	265.5		
				2.0	258.8	99.1	441.1		
	100.0	50	0.50	0.5	28.5	21.5	65.3		
				1.0	102.6	62.1	233.6		
				1.5	239.2	104.7	463.7		
				2.0	451.0	148.9	687.3		

Tow Speed^2 (knots^2)	95th Perc. Tension versus Tow Speed^4	
0.250	slope	90.26
1.012	error	1.86
2.248	rsquared	1.00
4.047	Cd	1.14
0.244	slope	52.33
1.020	error	2.06
2.234	rsquared	0.99
4.147	Cd	1.10
0.244	slope	59.25
1.003	error	1.22
2.230	rsquared	1.00
4.077	Cd	1.25
0.266	slope	105.81
1.006	error	4.35
2.240	rsquared	0.99
4.177	Cd	1.33
0.247	slope	146.38
1.020	error	8.87
2.347	rsquared	0.96
4.041	Cd	1.85
0.257	slope	96.38
1.012	error	8.84
2.338	rsquared	0.91
4.093	Cd	2.03
0.252	slope	99.87
0.988	error	8.41
2.231	rsquared	0.92
4.115	Cd	2.10
0.256	slope	149.58
1.008	error	12.01
2.268	rsquared	0.93
4.152	Cd	1.89
0.247	slope	158.10
0.981	error	6.67
2.276	rsquared	0.98
4.091	Cd	1.99
0.259	slope	95.86
1.001	error	6.27
2.246	rsquared	0.95
4.086	Cd	2.01
0.260	slope	112.45
1.001	error	5.34
2.224	rsquared	0.98
4.070	Cd	2.36
0.245	slope	185.21
0.958	error	10.32
2.276	rsquared	0.97
3.924	Cd	2.34

Wave Height (in.)	Cd
0	1.1
7.3	1.8
12.3	2.0
0	1.1
7.3	2.0
12.3	2.0
0	1.2
7.3	2.1
12.3	2.4
0	1.3
7.3	1.9
12.3	2.3
Kh	0.081

CCG 24 in. Curtain Boom - Summary Page

	Section	Length (ft)	Total Height (in.)	Draft (in.)	Free-board (in.)	Buoy. to wt.
Boom Characteristics	1	50.00	24	11	13	?
	2	50.00				
	3	50.00				

	Length (ft)	Gap (ft)	Gap Ratio	Tow Speed (knots)	Tension Average (lb_f)	Tension Std. Dev. (lb_f)	95th Perc. (lb_f)	Change in Draft Apex (in.)	Change in Draft Arm (in.)
Calm Runs	150.0	50	0.33	0.5	17.6	3.4	22.5	-0.7	0.6
				1.0	80.1	5.5	88.4	-0.7	2.6
				1.5	177.2	10.7	194.5	-1.4	2.8
				2.0	341.6	31.0	412.9	-1.8	1.9
	150.0	30	0.20	0.5	15.1	3.3	18.8	0.6	0.1
				1.0	56.2	4.8	63.9	0.4	3.3
				1.5	113.7	4.6	120.1	0.2	6.8
				2.0	198.2	8.2	212.9	0.0	9.5
	100.0	30	0.30	0.5	18.8	3.4	23.7	0.2	0.1
				1.0	70.4	4.8	77.4	0.5	-0.2
				1.5	118.8	5.0	127.4	0.6	-1.3
				2.0	218.6	7.1	229.9	0.9	-2.1
	100.0	50	0.50	0.5	19.6	2.6	22.5	0.2	0.4
				1.0	80.5	5.5	89.6	0.5	0.1
				1.5	179.7	6.7	192.0	-0.8	-4.7
				2.0	328.7	11.5	347.0	-0.7	-3.3
Regular Wave Runs	150.0	50	0.33	0.5	25.2	9.9	43.2		
				1.0	84.9	37.9	150.6		
				1.5	185.0	64.0	299.5		
				2.0	340.6	99.6	500.7		
	150.0	30	0.20	0.5	17.4	6.8	29.9		
				1.0	60.0	27.6	105.4		
				1.5	110.6	39.7	175.0		
				2.0	194.4	56.0	300.7		
	100.0	30	0.30	0.5	18.5	9.8	36.0		
				1.0	58.1	28.8	107.9		
				1.5	121.5	58.5	219.0		
				2.0	205.8	62.7	304.3		
	100.0	50	0.50	0.5	28.2	18.3	60.3		
				1.0	94.4	46.3	183.5		
				1.5	202.5	86.1	340.9		
				2.0	346.2	65.8	443.4		
Harbor Chop Runs	150.0	50	0.33	0.5	28.3	17.4	59.1		
				1.0	105.4	53.7	206.8		
				1.5	191.6	73.1	333.8		
				2.0	370.5	106.3	561.8		
	150.0	30	0.20	0.5	19.9	13.5	43.2		
				1.0	66.4	25.0	112.8		
				1.5	118.8	42.9	197.0		
				2.0	223.6	71.1	369.0		
	100.0	30	0.30	0.5	16.0	14.8	42.0		
				1.0	67.2	32.7	132.2		
				1.5	132.1	55.7	226.3		
				2.0	243.0	89.1	411.6		
	100.0	50	0.50	0.5	28.5	19.1	62.8		
				1.0	112.7	56.1	230.0		
				1.5	229.8	80.6	367.8		
				2.0	482.8	149.7	776.4		

Tow Speed^2 (knots^2)	95th Perc. Tension versus Tow Speed^2	
0.255	slope	96.47
1.064	error	3.52
2.231	rsquared	0.99
4.125	Cd	1.49
0.266	slope	54.23
0.994	error	1.39
2.253	rsquared	0.99
3.955	Cd	1.40
0.262	slope	57.24
1.096	error	2.10
2.258	rsquared	0.99
4.076	Cd	1.48
0.258	slope	85.68
1.015	error	0.33
2.240	rsquared	1.00
4.058	Cd	1.33
0.261	slope	123.82
1.000	error	4.05
2.323	rsquared	0.99
4.155	Cd	1.92
0.259	slope	75.99
0.997	error	3.93
2.288	rsquared	0.97
4.069	Cd	1.96
0.258	slope	81.46
1.026	error	6.04
2.292	rsquared	0.94
4.047	Cd	2.10
0.252	slope	121.46
1.012	error	12.14
2.342	rsquared	0.88
4.058	Cd	1.88
0.259	slope	144.64
1.101	error	6.66
2.292	rsquared	0.98
3.994	Cd	2.24
0.259	slope	90.45
1.003	error	3.68
2.257	rsquared	0.98
4.110	Cd	2.33
0.252	slope	102.82
1.032	error	3.93
2.298	rsquared	0.99
4.023	Cd	2.65
0.241	slope	184.51
1.027	error	8.72
2.288	rsquared	0.98
4.104	Cd	2.86

Wave Height (in.)	Cd
0	1.5
7.3	1.9
12.3	2.2
0	1.4
7.3	2.0
12.3	2.3
0	1.5
7.3	2.1
12.3	2.7
0	1.3
7.3	1.9
12.3	2.9
Kh	0.088

CCG 18 in. Fence Boom - Summary Page

	Section	Length (ft)	Total Height (in.)	Draft (in.)	Free-board (in.)	Buoy. to wt.
Boom Characteristics	1	49.83	18	11	7	3
	2	49.83				
	3	49.83				

	Length (ft)	Gap (ft)	Gap Ratio	Tow Speed (knots)	Tension Average (lb_f)	Tension Std. Dev. (lb_f)	Tension 95th Perc. (lb_f)	Change in Draft Apex (in.)	Change in Draft Arm (in.)
Calm Runs	150.0	45	0.30	0.5	12.0	2.9	15.1	0.0	0.7
				1.0	50.4	3.8	55.4	0.1	1.8
				1.5	110.3	5.9	122.5	-0.7	1.5
				2.0	205.2	8.2	221.3	-1.1	0.9
	150.0	30	0.20	0.5	7.2	3.0	10.3	-0.2	0.7
				1.0	37.7	3.8	43.2	-0.3	1.5
				1.5	87.8	4.0	94.4	-1.1	1.9
				2.0	151.3	7.6	165.2	-1.8	1.9
	100.0	30	0.30	0.5	10.4	3.5	15.1	0.6	0.2
				1.0	44.1	4.1	50.5	1.0	-0.5
				1.5	91.0	5.2	99.3	1.2	-1.8
				2.0	382.1	102.2	559.2	-45.4	-51.7
	100.0	50	0.50	0.5	19.9	4.2	26.1	0.8	0.2
				1.0	73.8	9.9	85.9	0.7	-0.6
				1.5	205.6	12.5	225.0	-10.4	-17.5
				2.0	632.2	103.2	831.2	-90.0	-89.6
Regular Wave Runs	150.0	45	0.30	0.5	12.9	7.1	22.5		
				1.0	53.6	21.1	89.6		
				1.5	118.8	47.9	198.3		
				2.0	419.5	173.3	689.8		
	150.0	30	0.20	0.5	11.1	7.2	26.1		
				1.0	41.6	23.0	83.5		
				1.5	89.8	41.4	159.2		
				2.0	441.0	130.4	697.1		
	100.0	30	0.30	0.5	10.2	9.7	29.8		
				1.0	44.0	33.4	101.8		
				1.5	248.8	79.8	367.8		
				2.0	452.2	82.8	632.5		
	100.0	50	0.50	0.5	20.1	13.4	43.2		
				1.0	80.7	43.2	161.6		
				1.5	430.8	78.8	580.1		
				2.0	520.2	58.1	632.4		
Harbor Chop Runs	150.0	45	0.30	0.5	18.3	13.5	40.7		
				1.0	67.0	32.0	124.9		
				1.5	172.8	82.8	316.6		
				2.0	541.0	101.7	758.3		
	150.0	30	0.20	0.5	15.6	10.4	35.9		
				1.0	48.4	37.3	100.5		
				1.5	111.7	56.2	215.2		
				2.0	475.6	101.5	681.6		
	100.0	30	0.30	0.5	13.8	10.7	34.7		
				1.0	54.0	32.7	116.4		
				1.5	311.2	90.3	466.6		
				2.0	436.2	94.3	637.4		
	100.0	50	0.50	0.5	23.7	19.9	63.9		
				1.0	90.9	41.7	159.1		
				1.5	430.0	78.6	572.8		
				2.0	535.8	65.0	662.9		

Tow Speed^2 (knots^2)	95th Perc. Tension versus Tow Speed^2	
0.265	slope	54.83
1.019	error	0.32
2.273	rsquared	1.00
4.013	Cd	0.94
0.250	slope	41.03
1.003	error	0.27
2.291	rsquared	1.00
4.045	Cd	1.06
0.251	slope	45.37
0.993	error	2.07
2.252	rsquared	0.99
4.072	Cd	1.17
0.260	slope	95.62
0.975	error	2.22
2.323	rsquared	1.00
3.919	Cd	1.48
0.248	slope	150.65
1.053	error	23.76
2.270	rsquared	0.87
3.891	Cd	2.59
0.255	slope	142.01
0.982	error	25.39
2.335	rsquared	0.84
4.123	Cd	3.66
0.255	slope	151.43
1.023	error	16.84
2.263	rsquared	0.94
3.972	Cd	3.91
0.248	slope	242.09
0.988	error	25.00
2.247	rsquared	0.95
4.046	Cd	3.75
0.259	slope	172.52
0.998	error	12.16
2.255	rsquared	0.97
4.096	Cd	2.97
0.257	slope	150.76
0.996	error	19.70
2.263	rsquared	0.90
3.960	Cd	3.89
0.269	slope	191.54
1.023	error	25.69
2.236	rsquared	0.92
3.978	Cd	4.94
0.252	slope	242.19
0.988	error	25.41
2.219	rsquared	0.95
4.106	Cd	3.75

Wave Height (in.)	Cd
0	0.9
7.3	2.6
12.3	3.0
0	1.1
7.3	3.7
12.3	3.9
0	1.2
7.3	3.9
12.3	4.9
0	1.5
7.3	3.7
12.3	3.7
Kh	0.228

CCG 36 in. Fence Boom - Summary Page

	Section	Length (ft)	Total Height (in.)	Draft (in.)	Free-board (in.)	Buoy. to wt.
Boom Characteristics	1	49.75	36	24	12	3
	2	49.75				
	3	49.75				

	Length (ft)	Gap (ft)	Gap Ratio	Tow Speed (knots)	Tension Average (lb_f)	Tension Std. Dev. (lb_f)	Tension 95th Perc. (lb_f)	Change in Draft Apex (in.)	Change in Draft Arm (in.)
Calm Runs	150.0	45	0.30	0.5	55.9	5.0	62.7	-0.2	0.8
				1.0	240.9	9.0	254.3	-1.5	0.3
				1.5	1589.3	344.6	2262.3	-59.1	-23.5
				2.0	1871.0	392.9	2266.0	-59.5	-44.5
	150.0	30	0.20	0.5	42.8	6.9	55.4	0.2	-0.2
				0.7	110.5	13.3	129.8	-0.7	0.1
				1.0	213.8	33.8	242.1	-1.2	0.8
	100.0	30	0.30	0.3	11.9	2.6	16.4	-0.7	-0.5
				0.7	62.3	2.6	65.8	-1.5	-0.5
				1.0	201.4	7.3	212.8	-0.2	-1.0
	100.0	50	0.50	0.5	70.8	5.7	79.8	-21.0	-23.8
				0.8	164.7	7.2	177.4	-18.6	-22.8
				1.0	298.0	13.3	317.8	-20.5	-23.1
Regular Wave Runs	150.0	45	0.30	0.5	69.8	35.9	139.6		
				1.0	358.6	128.2	605.9		
				1.5	1419.6	449.8	2262.3		
				2.0	1963.6	326.1	2267.2		
	150.0	30	0.20	0.5	43.0	19.1	79.8		
				0.7	104.6	58.1	198.3		
				1.0	177.0	101.7	298.2		
	100.0	30	0.30	0.5	45.5	22.2	83.5		
				0.8	114.1	49.8	189.6		
				1.0	220.0	77.1	350.8		
	100.0	50	0.50	0.5	73.7	27.8	121.3		
				0.7	163.1	57.7	266.5		
				1.0	411.5	124.3	631.8		
Harbor Chop Runs	150.0	45	0.30	0.5	54.3	27.0	101.8		
				1.0	337.1	146.1	626.3		
				1.5	1682.0	447.6	2264.7		
				2.0	1873.8	382.1	2267.2		
	150.0	30	0.20	0.5	50.7	37.0	121.7		
				0.7	107.5	65.8	240.9		
				1.0	226.1	89.0	386.0		
	100.0	30	0.30	0.5	50.2	30.4	107.9		
				0.8	117.2	54.3	217.7		
				1.0	230.8	88.5	389.7		
	100.0	50	0.50	0.5	73.3	39.6	147.0		
				0.8	188.5	72.6	328.8		
				1.0	490.2	193.1	868.4		

Tow Speed^2 (knots^2)	95th Perc. Tension versus Tow Speed^4	
0.254	slope	243.68
1.044	error	0.72
2.324	rsquared	1.00
4.144	Cd	1.92
0.244	slope	237.80
0.562	error	3.29
1.006	rsquared	1.00
0.000	Cd	2.81
0.064	slope	190.89
0.556	error	28.42
1.000	rsquared	0.90
0.000	Cd	2.25
0.253	slope	314.74
0.579	error	3.42
1.001	rsquared	1.00
0.000	Cd	2.23
0.245	slope	576.07
1.051	error	1.20
2.190	rsquared	1.00
3.856	Cd	4.54
0.254	slope	309.10
0.562	error	16.98
1.010	rsquared	0.97
0.000	Cd	3.65
0.244	slope	338.53
0.591	error	7.12
1.019	rsquared	1.00
0.000	Cd	4.00
0.247	slope	573.50
0.560	error	39.65
1.042	rsquared	0.97
0.000	Cd	4.07
0.249	slope	604.51
1.016	error	47.98
2.379	rsquared	0.98
4.000	Cd	4.76
0.261	slope	403.08
0.551	error	17.47
0.994	rsquared	0.98
0.000	Cd	4.76
0.250	slope	394.47
0.581	error	9.31
0.977	rsquared	0.99
0.000	Cd	4.66
0.254	slope	782.98
0.580	error	95.85
0.999	rsquared	0.91
0.000	Cd	5.55

Wave Height (in.)	Cd
0	1.9
7.3	4.5
12.3	4.8
0	2.8
7.3	3.7
12.3	4.8
0	2.3
7.3	4.0
12.3	4.7
0	2.2
7.3	4.1
12.3	5.6
Kh	0.216

USCG Oil-Stop Boom - Summary Page

	Section	Length (ft)	Total Height (in.)	Draft (in.)	Free-board (in.)	Buoy. to wt.
Boom Characteristics	1	10.33	47.0	30.0	17.0	20
	2	10.33				
	3	10.33				

	Length (ft)	Gap (ft)	Gap Ratio	Tow Speed (knots)	Tension Average (lb_f)	Tension Std. Dev. (lb_f)	Tension 95th Perc. (lb_f)	Change in Draft Apex (in.)	Change in Draft Arm (in.)
Calm Runs	164.0	50	0.30	0.5	74.3	4.5	81.0	1.5	-0.5
				1.0	259.3	9.2	273.8	2.6	0.0
				1.5	524.1	19.8	549.5	4.4	1.2
				2.0	897.1	21.4	931.3	4.0	2.3
	164.0	33	0.20	0.5	51.1	6.4	61.5	2.4	0.1
				1.0	200.0	9.5	215.2	2.6	0.3
				1.5	372.2	20.3	403.1	4.3	0.0
				2.0	676.7	11.3	693.4	4.0	0.9
	82.0	25	0.30	0.5	44.8	4.5	50.5	1.5	-0.2
				1.0	148.2	7.4	160.3	1.8	2.1
				1.5	295.3	10.8	314.0	2.2	1.9
				2.0	499.1	11.9	520.2	2.4	1.0
	82.0	41	0.50	0.5	66.4	4.0	72.5	2.0	0.9
				1.0	232.0	5.6	240.8	2.9	1.9
				1.5	468.1	11.7	486.1	-19.4	-21.4
				2.0	744.4	13.8	769.1	-14.7	-21.5
Regular Wave Runs	164.0	50	0.30	0.5	88.7	22.8	128.6		
				1.0	273.2	61.0	359.2		
				1.5	561.8	92.4	725.7		
				2.0	971.4	184.3	1337.4		
	164.0	33	0.20	0.5	74.1	22.5	111.6		
				1.0	195.7	45.1	261.6		
				1.5	409.1	96.2	589.9		
				2.0	701.1	173.3	1067.0		
	82.0	25	0.30	0.5	53.9	13.7	79.8		
				1.0	151.7	54.8	247.0		
				1.5	334.7	95.2	499.8		
				2.0	557.4	132.8	827.6		
	82.0	41	0.50	0.5	78.9	23.3	116.4		
				1.0	222.8	52.7	304.3		
				1.5	478.8	115.5	680.2		
				2.0	793.9	187.4	1142.6		
Harbor Chop Runs	164.0	50	0.30	0.5	85.3	27.9	135.9		
				1.0	290.4	71.3	430.1		
				1.5	526.6	98.8	702.0		
				2.0	1004.7	179.9	1341.4		
	164.0	33	0.20	0.5	66.9	27.2	115.3		
				1.0	218.2	49.3	303.4		
				1.5	397.2	91.2	555.8		
				2.0	696.4	139.2	976.6		
	82.0	25	0.30	0.5	51.0	34.1	99.4		
				1.0	159.8	64.5	267.7		
				1.5	327.0	95.7	504.5		
				2.0	570.1	138.8	833.7		
	82.0	41	0.50	0.5	87.7	45.4	171.5		
				1.0	248.9	72.5	378.6		
				1.5	467.5	123.0	655.6		
				2.0	791.8	167.3	1112.1		

Tow Speed^2 (knots^2)	95th Perc. Tension versus Tow Speed^2	
0.253	slope	234.26
0.988	error	7.09
2.245	rsquared	0.99
4.081	Cd	1.33
0.254	slope	173.36
1.006	error	5.82
2.270	rsquared	0.99
4.095	Cd	1.49
0.250	slope	134.32
1.019	error	4.39
2.232	rsquared	0.99
3.985	Cd	1.52
0.254	slope	199.96
0.999	error	8.09
2.257	rsquared	0.98
4.003	Cd	1.38
0.256	slope	321.88
0.991	error	7.55
2.307	rsquared	1.00
4.164	Cd	1.83
0.255	slope	258.83
1.018	error	5.63
2.320	rsquared	1.00
4.108	Cd	2.23
0.259	slope	211.07
0.988	error	6.84
2.263	rsquared	0.99
4.032	Cd	2.40
0.259	slope	279.51
1.005	error	7.69
2.316	rsquared	0.99
4.182	Cd	1.93
0.249	slope	327.37
1.012	error	14.09
2.241	rsquared	0.98
4.129	Cd	1.86
0.256	slope	242.79
1.032	error	9.33
2.265	rsquared	0.99
4.104	Cd	2.09
0.248	slope	213.10
1.004	error	10.33
2.216	rsquared	0.98
4.070	Cd	2.42
0.255	slope	281.57
1.016	error	17.00
2.290	rsquared	0.96
4.075	Cd	1.95

Wave Height (in.)	Cd
0	1.3
7.3	1.8
12.3	1.9
0	1.5
7.3	2.2
12.3	2.1
0	1.5
7.3	2.4
12.3	2.4
0	1.4
7.3	1.9
12.3	1.9
Kh	0.055

CCG Ro-Boom - Summary Page

	Section	Length (ft)	Total Height (in.)	Draft (in.)	Free-board (in.)	Buoy. to wt.
Boom Characteristics	1	98.00	78.5	44.5	34	20
	2	98.00	(connector)	(inflated)		

	Length (ft)	Gap (ft)	Gap Ratio	Tow Speed (knots)	Tension Average (lb_f)	Tension Std. Dev. (lb_f)	Tension 95th Perc. (lb_f)	Change in Draft Apex (in.)	Change in Draft Arm (in.)
Calm Runs	196.0	59	0.30	0.5	277.6	16.6	298.2	-1.4	-0.6
				1.0	1318.8	105.9	1462.0	0.6	-1.3
				1.2	1287.6	102.8	1467.4	0.9	-1.1
				1.5	2627.9	105.3	2770.6	-0.6	-5.0
	196.0	39	0.20	0.5	180.2	14.2	193.8	-6.0	0.5
				1.0	727.5	59.3	779.4	-4.2	0.2
				1.5	1112.3	177.7	1404.4	-2.3	0.1
				1.7	1840.2	387.0	2590.2	-1.7	-0.6
	98.0	30	0.31	0.5	147.7	6.5	157.2	-1.1	1.4
				1.0	539.6	16.7	564.7	0.5	1.9
				1.5	1005.3	63.8	1077.0	1.7	1.3
				1.7	1417.8	22.5	1452.9	2.2	1.6
	98.0	49	0.50	0.5	262.1	15.5	281.7	0.8	1.9
				1.0	754.6	17.7	784.3	1.4	1.7
				1.3	1108.8	33.0	1157.6	0.2	1.5
				1.5	1598.3	43.4	1665.2	-0.2	0.4
Regular Wave Runs	196.0	59	0.30	0.5	299.8	72.6	425.7		
				1.0	1130.4	122.8	1318.8		
				1.3	1504.3	367.2	2006.8		
				1.5	2586.9	385.9	3319.8		
	196.0	39	0.20	0.5	310.0	119.7	552.6		
				1.0	884.3	214.6	1346.2		
				1.5	1769.2	217.5	2180.3		
				1.8	2250.8	411.1	3072.7		
	98.0	30	0.31	0.5	197.1	38.5	266.9		
				1.0	654.9	118.3	855.2		
				1.5	1162.5	151.0	1399.3		
				1.7	1473.4	162.4	1811.4		
	98.0	49	0.50	0.5	332.6	68.7	445.1		
				1.0	871.3	163.4	1138.0		
				1.3	1263.4	196.0	1564.9		
				1.5	1811.9	222.9	2187.1		
Harbor Chop Runs	196.0	59	0.30	0.5	317.2	56.1	415.9		
				1.0	1300.2	135.1	1538.5		
				1.2	1640.0	215.7	2031.3		
				1.5	3060.9	442.9	3715.4		
	196.0	39	0.20	0.5	317.4	71.5	437.9		
				1.0	758.5	133.8	1016.4		
				1.5	1948.9	247.5	2402.0		
				1.7	2675.2	364.0	3298.1		
	98.0	30	0.31	0.5	218.6	44.2	294.1		
				1.0	662.7	131.7	901.3		
				1.5	1266.5	187.2	1594.7		
				1.8	1573.7	215.3	1936.1		
	98.0	49	0.50	0.5	340.3	74.0	477.2		
				1.0	913.1	147.9	1170.0		
				1.3	1320.5	222.4	1672.8		
				1.5	1901.1	289.5	2392.9		

Tow Speed^2 (knots^2)	95th Perc. Tension versus Tow Speed^2		
0.243	slope	1175.39	
0.977	error	97.99	
1.560	rsquared	0.92	
2.258	Cd	3.81	
0.262	slope	775.75	
0.964	error	58.77	
2.228	rsquared	0.95	
3.045	Cd	3.80	
0.251	slope	482.25	
1.019	error	12.41	
2.268	rsquared	0.99	
3.044	Cd	3.07	
0.252	slope	750.31	
0.995	error	20.30	
1.570	rsquared	0.99	
2.236	Cd	2.93	
0.252	slope	1381.29	
0.989	error	47.36	
1.584	rsquared	0.99	
2.305	Cd	4.48	
0.254	slope	982.84	
1.028	error	65.76	
2.277	rsquared	0.94	
3.218	Cd	4.82	
0.250	slope	629.12	
0.999	error	39.32	
2.234	rsquared	0.95	
3.006	Cd	4.01	
0.255	slope	977.75	
0.998	error	53.15	
1.574	rsquared	0.95	
2.347	Cd	3.82	
0.244	slope	1555.33	
0.967	error	74.32	
1.509	rsquared	0.98	
2.265	Cd	5.04	
0.246	slope	1067.99	
1.039	error	29.88	
2.276	rsquared	0.99	
3.051	Cd	5.24	
0.255	slope	670.95	
1.009	error	42.34	
2.290	rsquared	0.95	
3.075	Cd	4.28	
0.252	slope	1072.75	
1.022	error	44.11	
1.564	rsquared	0.97	
2.279	Cd	4.19	

Wave Height (in.)	Cd
0	3.8
7.3	4.5
12.3	5.0
0	3.8
7.3	4.8
12.3	5.2
0	3.1
7.3	4.0
12.3	4.3
0	2.9
7.3	3.8
12.3	4.2
Kh	0.105

US Navy Boom - Summary Page

	Section	Length (ft)	Total Height (in.)	Draft (in.)	Free-board (in.)	Buoy. to wt.
Boom Characteristics	1	55.25	52.0	36.0	14.0	8
	2	55.42				
	3	55.25				

	Length (ft)	Gap (ft)	Gap Ratio	Tow Speed (knots)	Tension Average (lb_f)	Tension Std. Dev. (lb_f)	Tension 95th Perc. (lb_f)	Change in Draft Apex (in.)	Change in Draft Arm (in.)
Calm Runs	166.0	50	0.30	0.5	121.6	4.8	128.6	0.5	-2.1
				1.0	492.1	22.3	525.1	1.6	-1.5
				1.5	1037.7	98.3	1183.9	-0.1	-2.2
				2.0	2259.2	5.2	2263.5	-3.2	-8.0
	166.0	33	0.20	0.5	78.0	11.2	98.1	0.4	-2.5
				1.0	334.3	29.4	387.2	1.0	-2.2
				1.5	683.4	51.6	782.5	0.7	-1.5
				1.8	1056.2	41.0	1124.2	0.4	-2.1
	111.0	33	0.30	0.5	85.0	7.3	96.9	1.8	-3.6
				1.0	300.4	18.2	331.1	4.2	-3.5
				1.5	679.8	22.0	715.4	5.0	-5.9
				1.7	874.3	37.8	933.8	3.6	-7.6
	111.0	55.5	0.50	0.5	127.2	6.0	137.1	3.5	-4.6
				1.0	499.5	13.4	521.5	2.2	-5.2
				1.3	690.0	28.8	736.2	4.3	-6.0
				1.5	977.6	64.0	1089.9	3.8	-6.9
Regular Wave Runs	166.0	50	0.30	0.5	151.0	34.8	201.8		
				1.0	518.3	108.1	703.3		
				1.3	681.3	180.1	1064.7		
				1.5	1250.0	290.9	1762.3		
	166.0	33	0.20	0.5	88.0	16.8	122.6		
				1.0	325.1	101.7	500.7		
				1.5	673.7	157.1	960.7		
				1.7	1088.2	321.7	1638.1		
	111.0	33	0.30	0.5	96.1	24.2	137.2		
				1.0	287.0	79.2	436.3		
				1.5	660.0	159.5	926.6		
				1.8	868.0	291.0	1376.9		
	111.0	55.5	0.50	0.5	124.3	13.6	146.9		
				1.0	460.4	123.4	681.4		
				1.2	676.1	185.1	981.5		
				1.5	928.3	249.2	1353.5		
Harbor Chop Runs	166.0	50	0.30	0.5	140.6	30.5	198.1		
				1.0	512.6	119.8	736.2		
				1.3	719.5	156.1	1002.2		
				1.5	1213.2	243.9	1676.5		
	166.0	33	0.20	0.5	113.6	29.9	172.5		
				1.0	361.4	111.1	581.4		
				1.5	644.3	166.6	970.5		
				1.8	1116.0	306.3	1682.9		
	111.0	33	0.30	0.5	90.0	17.5	122.6		
				1.0	305.0	63.0	428.7		
				1.5	665.7	175.0	990.0		
				1.8	919.8	267.6	1388.2		
	111.0	55.5	0.50	0.5	150.2	39.6	231.1		
				1.0	547.4	148.1	829.3		
				1.2	701.5	171.3	1026.9		
				1.5	1019.4	269.7	1487.8		

Tow Speed^2 (knots^2)	95th Perc. Tension versus Tow Speed^2	
0.250	slope	552.57
0.993	error	10.37
2.265	rsquared	1.00
4.016	Cd	2.61
0.254	slope	359.77
1.004	error	6.74
2.270	rsquared	1.00
3.080	Cd	2.58
0.263	slope	311.90
0.996	error	5.06
2.248	rsquared	1.00
3.053	Cd	2.23
0.256	slope	484.71
0.989	error	9.98
1.571	rsquared	0.99
2.254	Cd	2.06
0.271	slope	726.61
1.028	error	20.90
1.565	rsquared	0.99
2.332	Cd	3.44
0.260	slope	506.51
0.992	error	34.45
2.256	rsquared	0.96
2.957	Cd	3.63
0.251	slope	422.55
1.002	error	11.81
2.345	rsquared	0.99
3.161	Cd	3.03
0.254	slope	608.61
0.962	error	22.87
1.562	rsquared	0.98
2.322	Cd	2.59
0.255	slope	695.52
0.978	error	29.60
1.624	rsquared	0.98
2.319	Cd	3.29
0.262	slope	512.80
1.009	error	30.61
2.223	rsquared	0.96
3.091	Cd	3.67
0.258	slope	443.52
0.978	error	3.10
2.266	rsquared	1.00
3.103	Cd	3.18
0.256	slope	681.99
1.039	error	28.19
1.560	rsquared	0.97
2.235	Cd	2.91

Wave Height (in.)	Cd
0	2.6
7.3	3.4
12.3	3.3
0	2.6
7.3	3.6
12.3	3.7
0	2.2
7.3	3.0
12.3	3.2
0	2.1
7.3	2.6
12.3	2.9
Kh	0.075

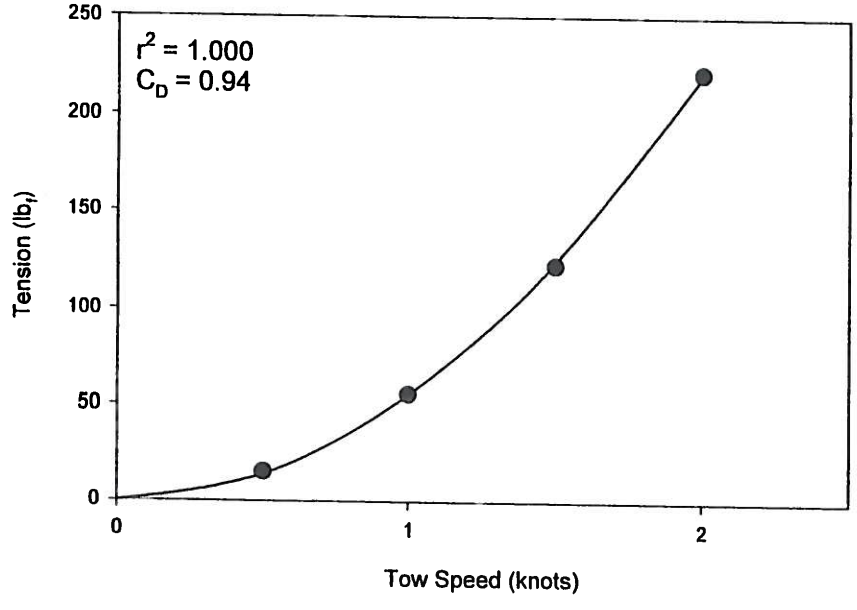
Appendix C:

Tow Force vs. Tow Speed Curves per Boom

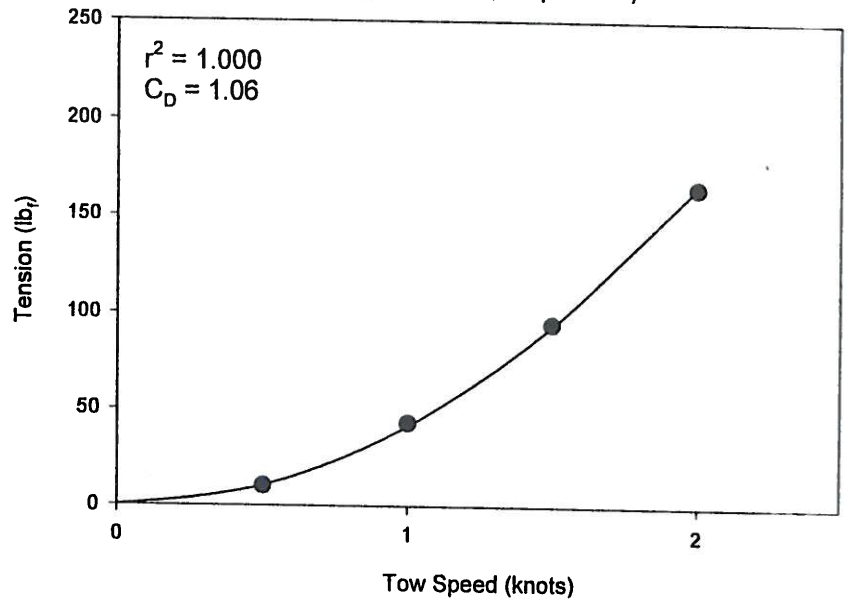
Figure C-1

CCG 18" Flexy Fence
Tow Speed vs Tension - Calm Conditions

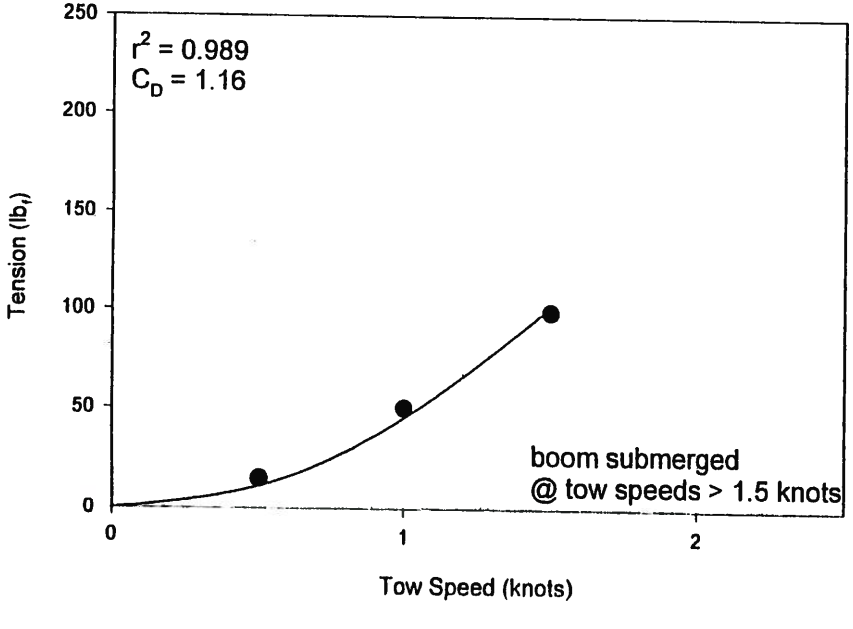
Gap Ratio = 0.30
(Length = 150ft, Gap = 45ft)



Gap Ratio = 0.20
(Length = 150ft, Gap = 30ft)



Gap Ratio = 0.30
(Length = 100ft, Gap = 30ft)



Gap Ratio = 0.50
(Length = 100ft, Gap = 50ft)

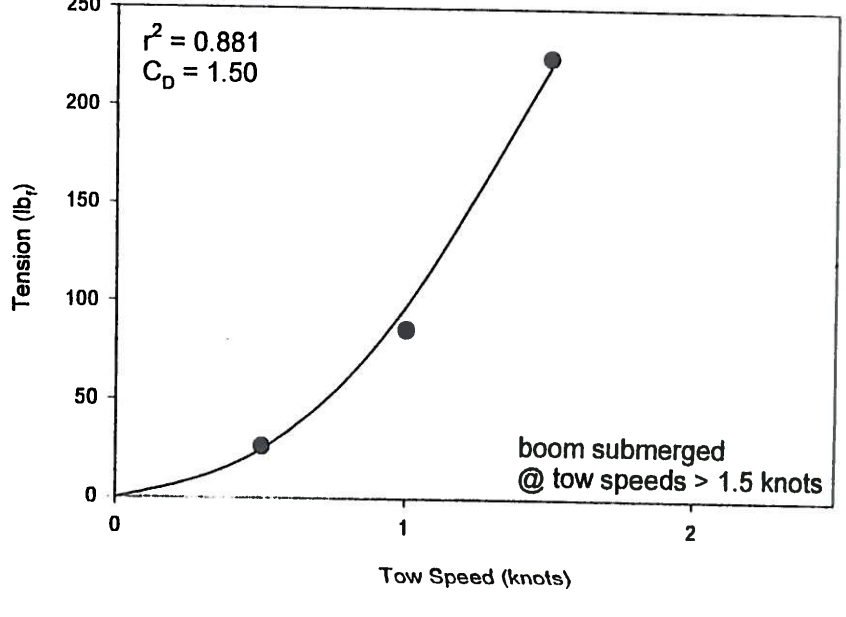
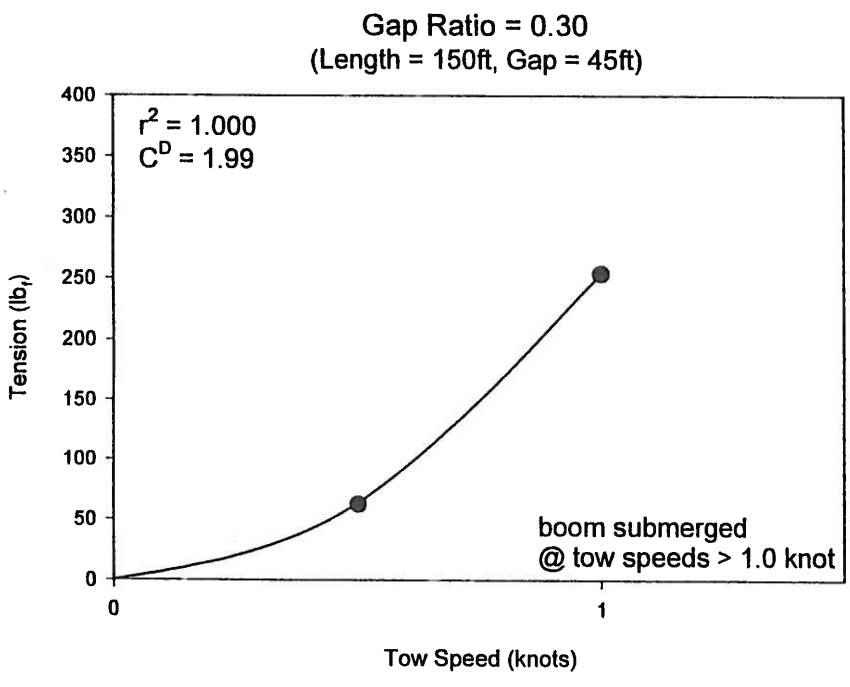
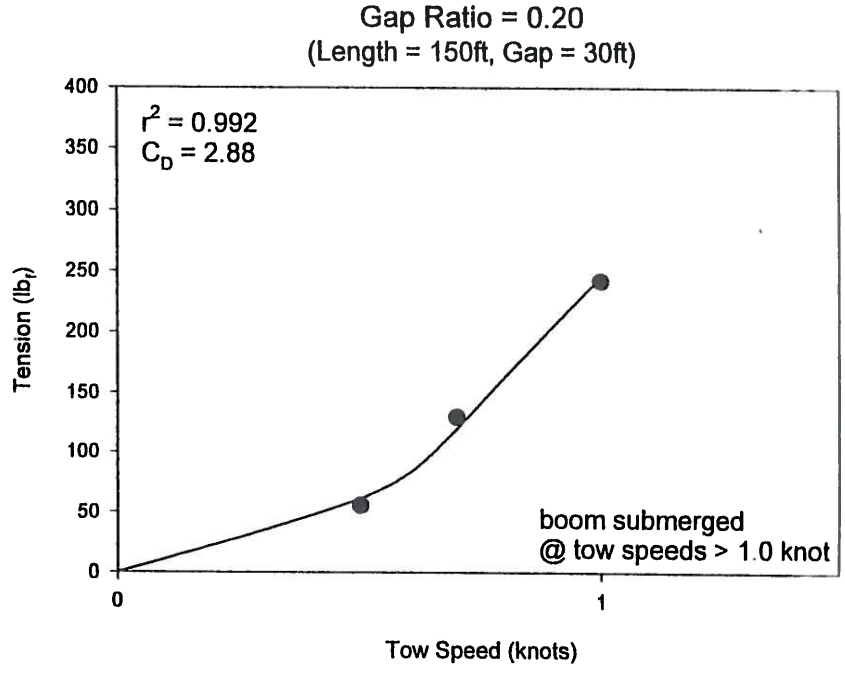


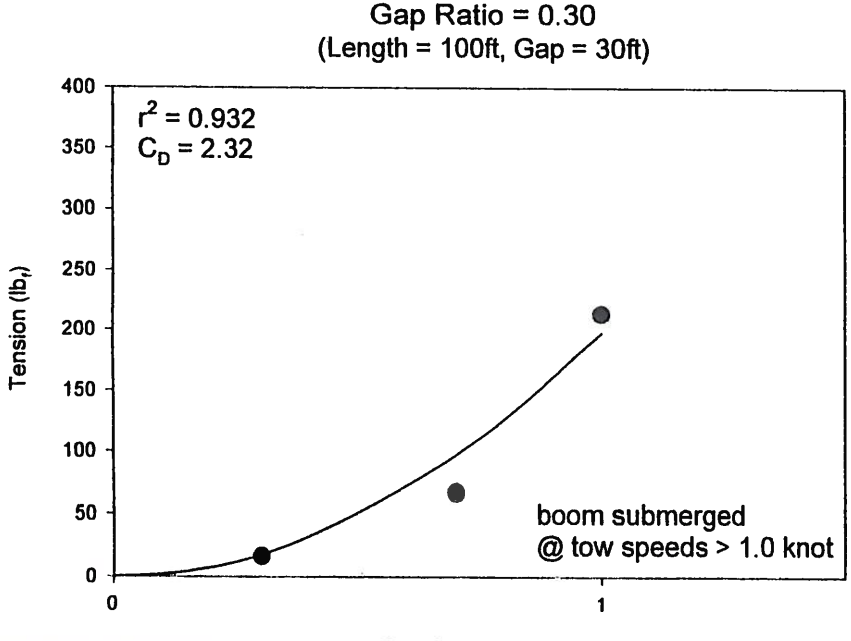
Figure C-2

CCG 36" Flexy Fence

Tow Speed vs Tension - Calm Conditions







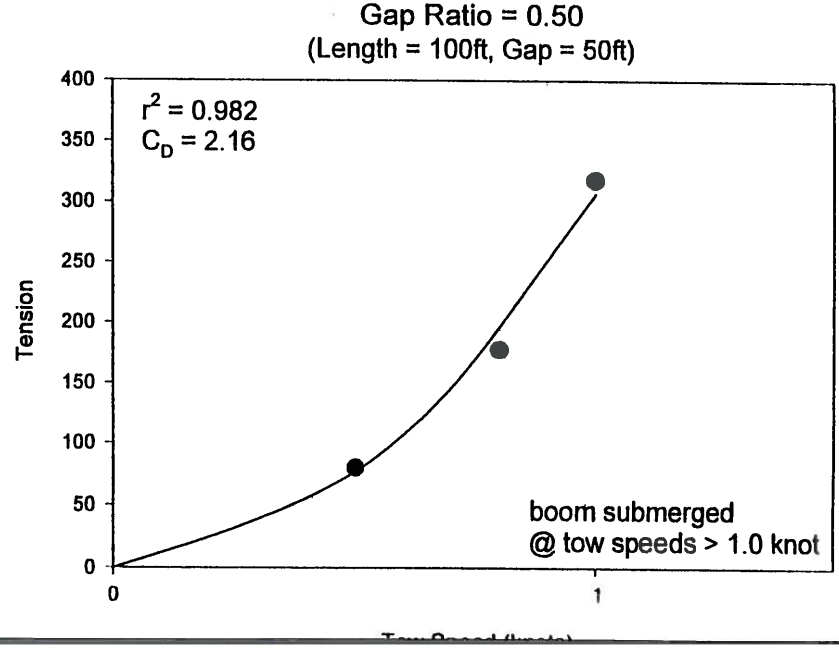
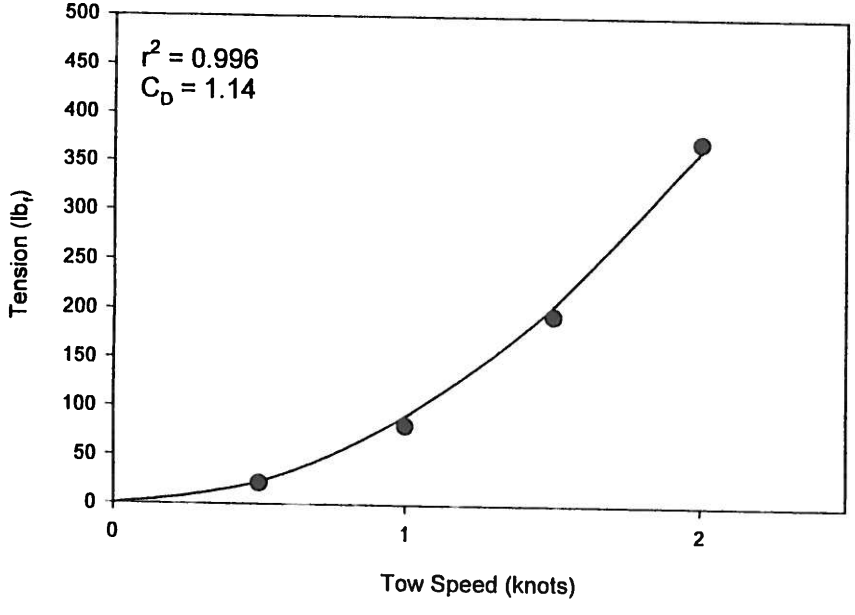


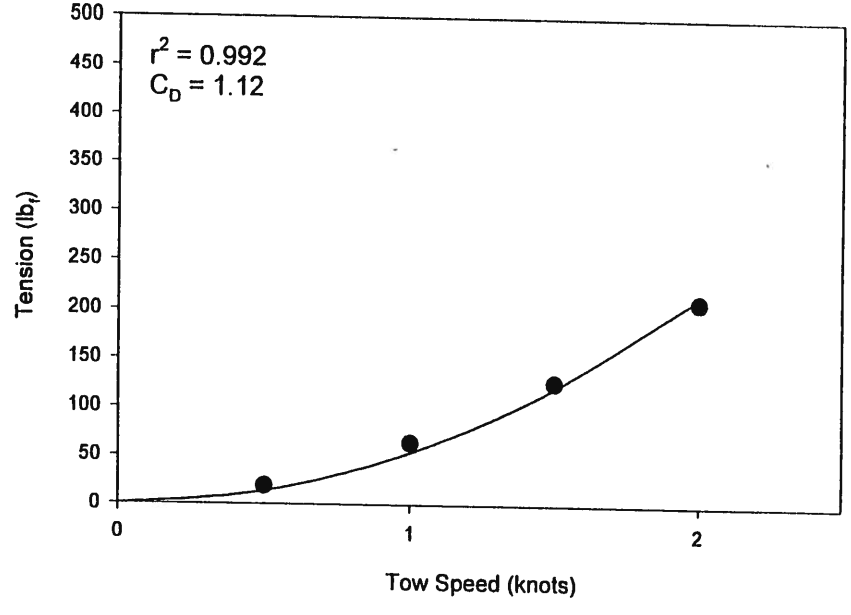
Figure C-5

CCG 18" Sanivan Curtain
Tow Speed vs Tension - Calm Conditions

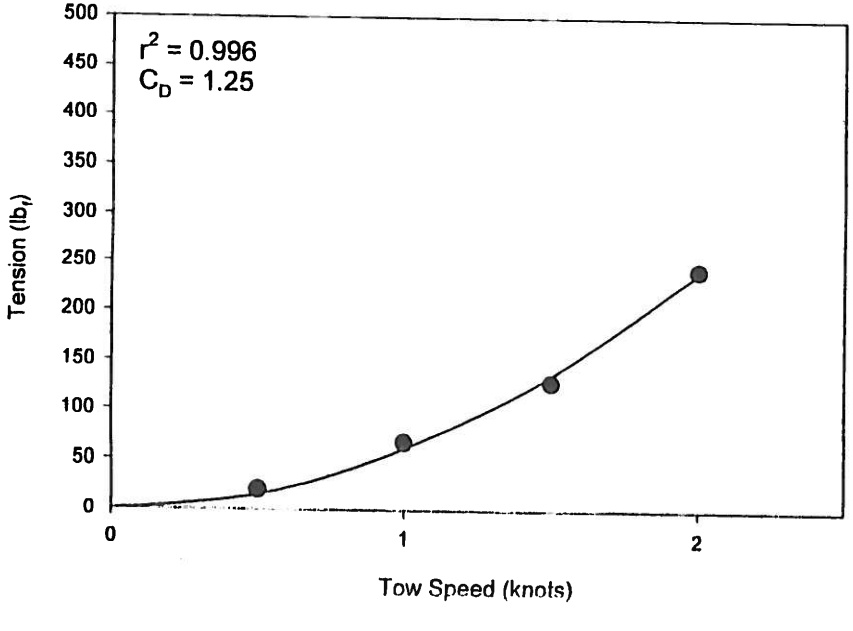
Gap Ratio = 0.33
(Length = 149.7ft, Gap = 50ft)



Gap Ratio = 0.20
(Length = 149.7ft, Gap = 30ft)



Gap Ratio = 0.30
(Length = 99.8ft, Gap = 30ft)



Gap Ratio = 0.50
(Length = 99.8ft, Gap = 50ft)

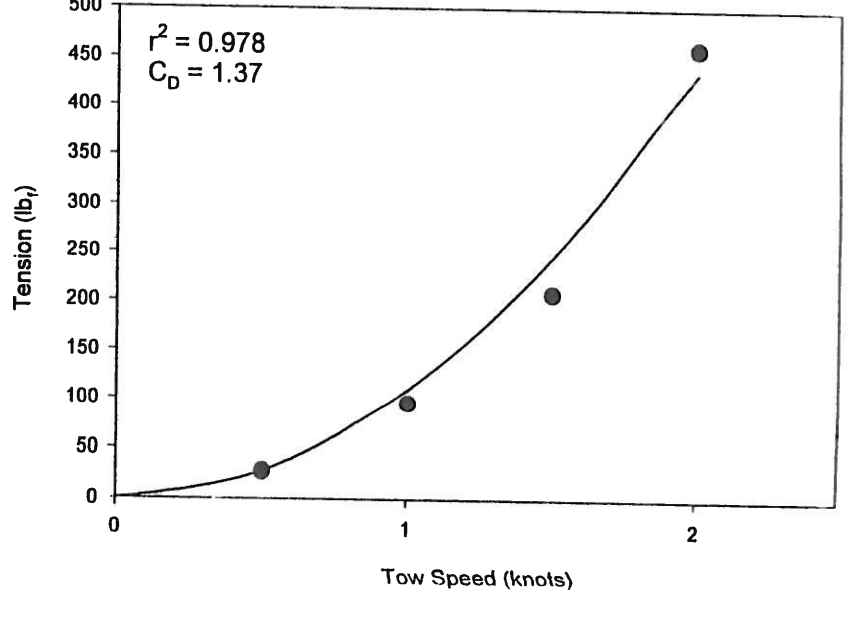
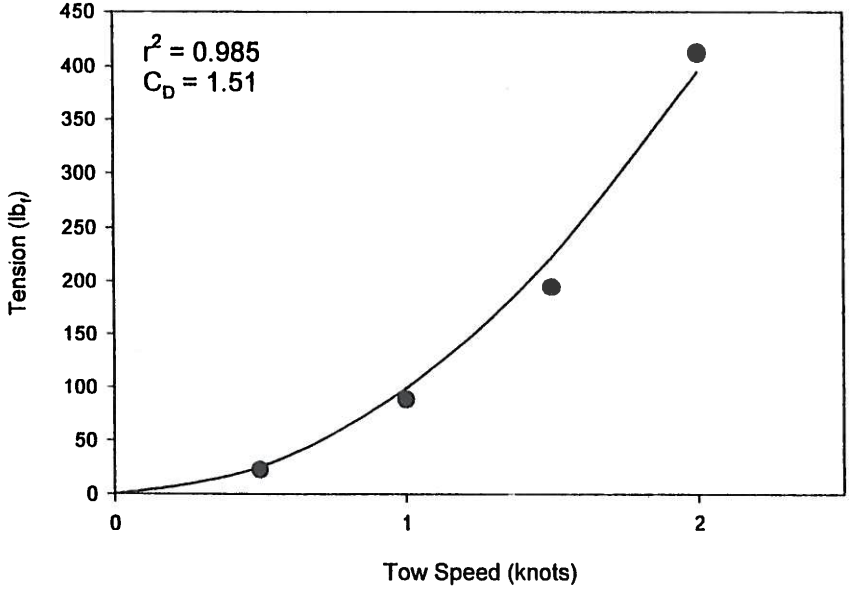


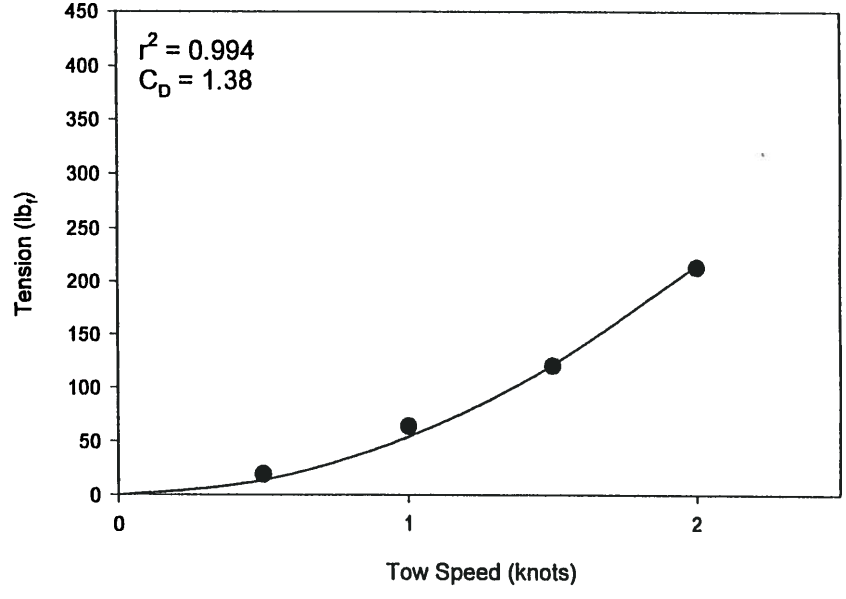
Figure C-4

CCG 24" Sanivan Curtain
Tow Speed vs Tension - Calm Conditions

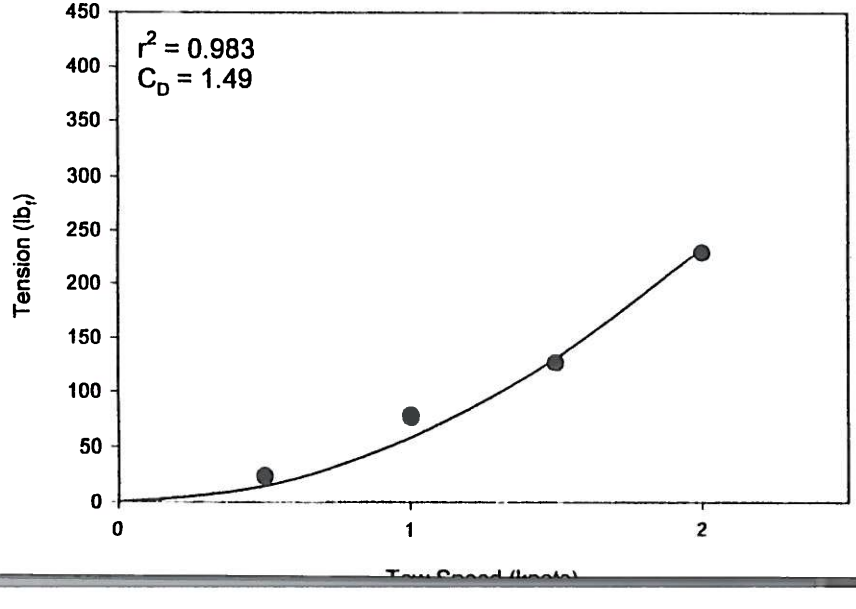
Gap Ratio = 0.33
(Length = 150ft, Gap = 50ft)



Gap Ratio = 0.20
(Length = 150ft, Gap = 30ft)



Gap Ratio = 0.30
(Length = 100ft, Gap = 30ft)



Gap Ratio = 0.50
(Length = 100ft, Gap = 50ft)

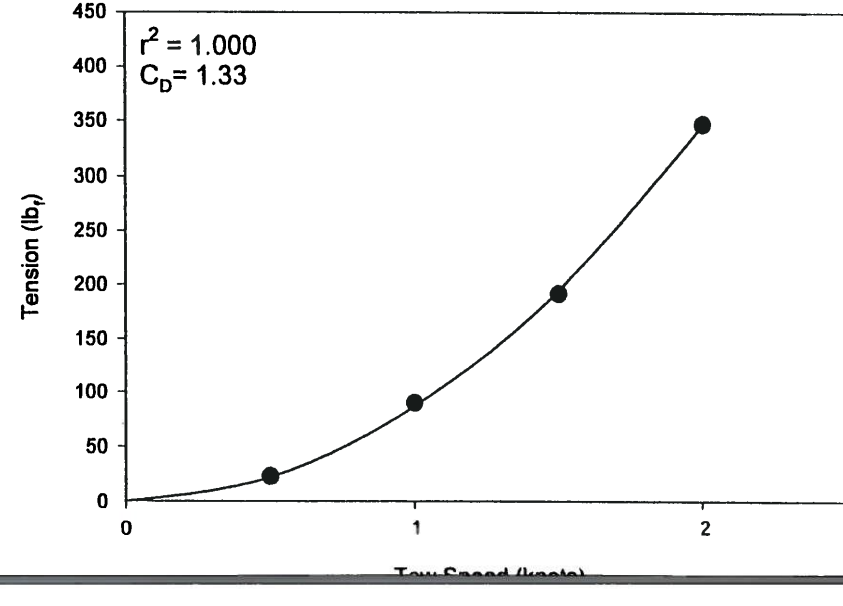
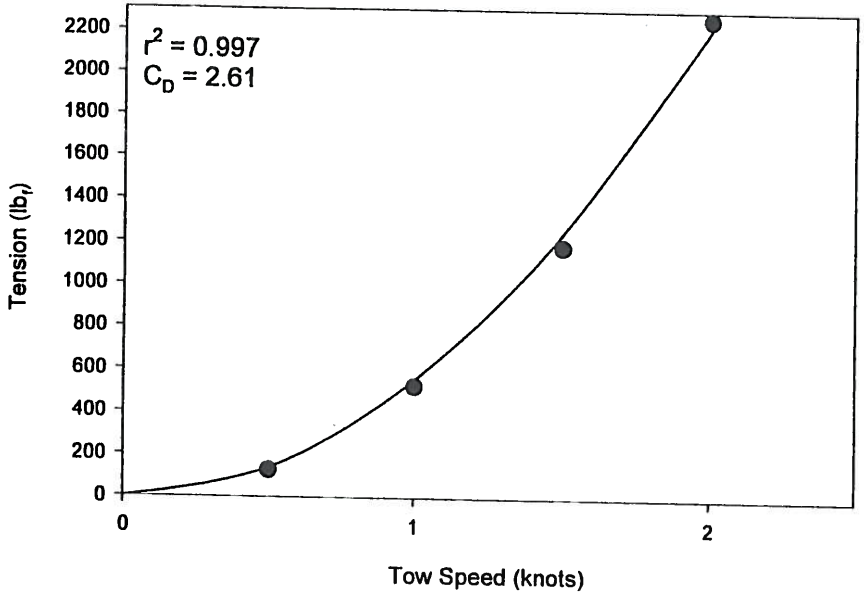


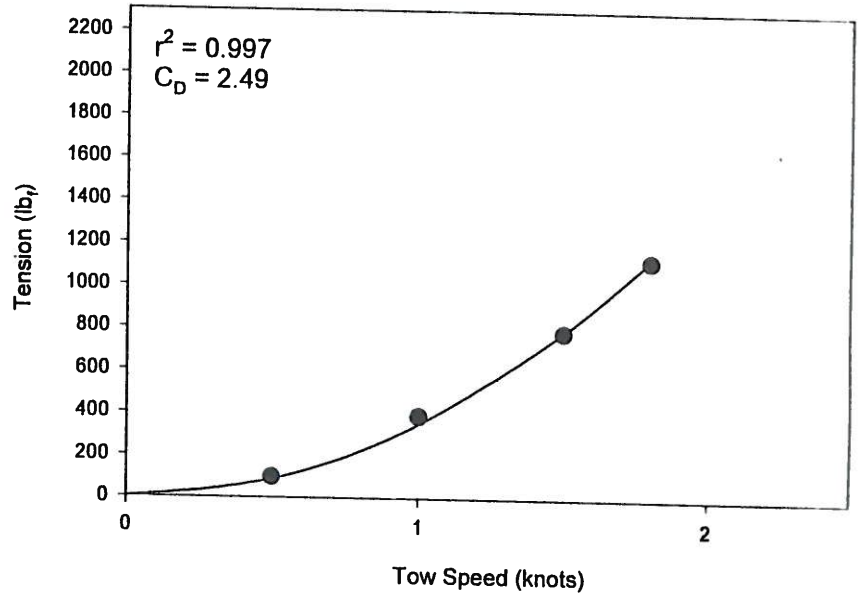
Figure C-5

US Navy USS-42 Inflatable
Tow Speed vs Tension - Calm Conditions

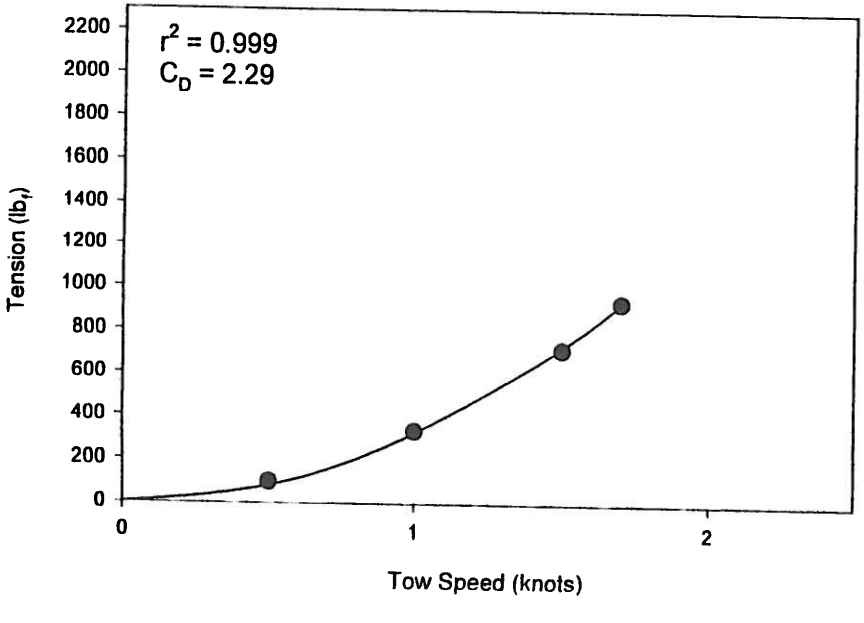
Gap Ratio = 0.30
(Length = 166ft, Gap = 50ft)



Gap Ratio = 0.20
(Length = 166ft, Gap = 33ft)



Gap Ratio = 0.30
(Length = 111ft, Gap = 30ft)



Gap Ratio = 0.50
(Length = 111ft, Gap = 55.5ft)

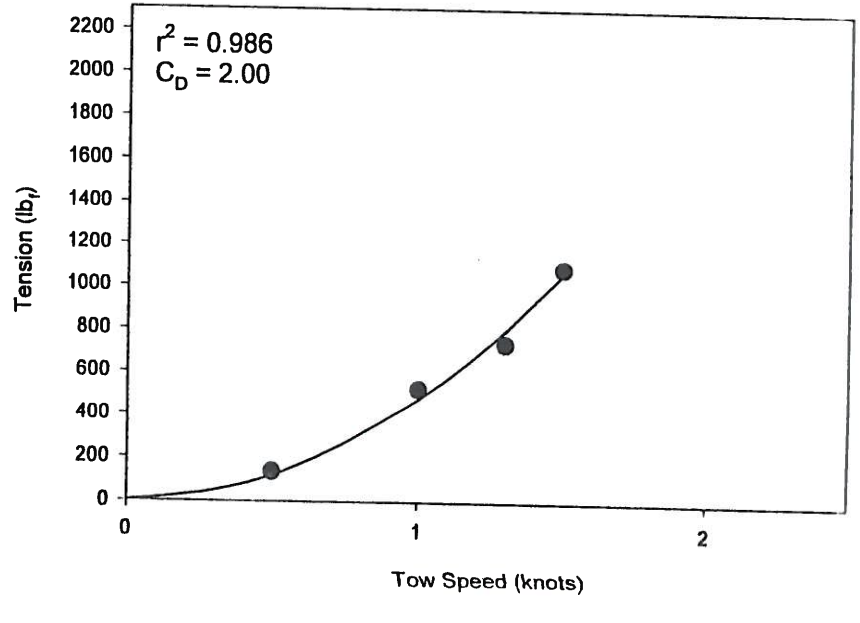
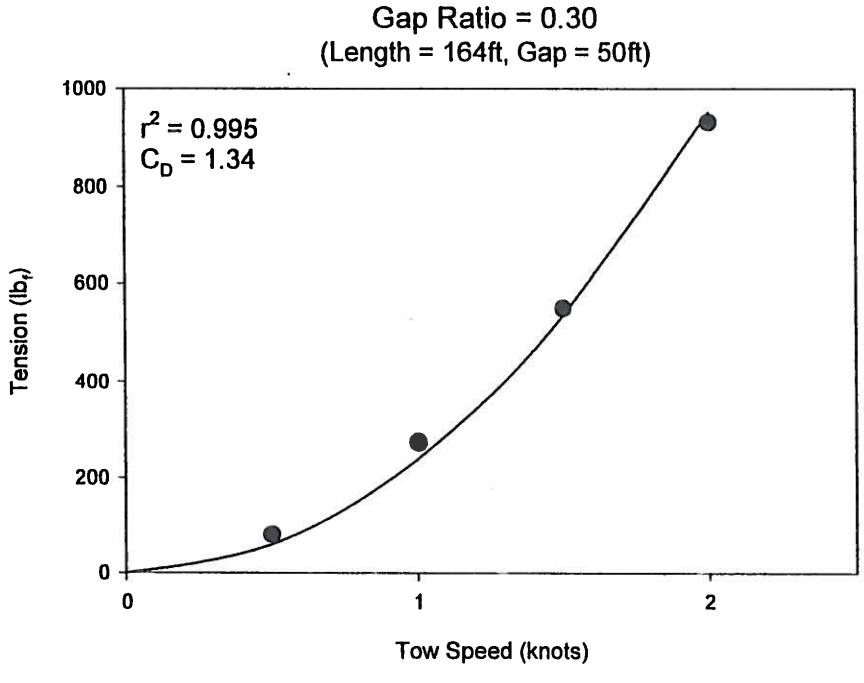
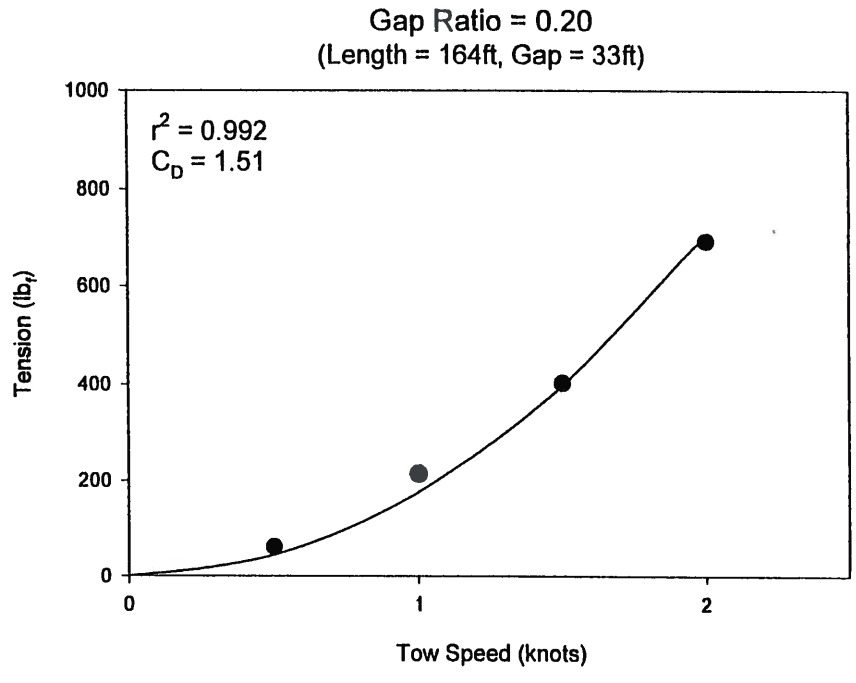
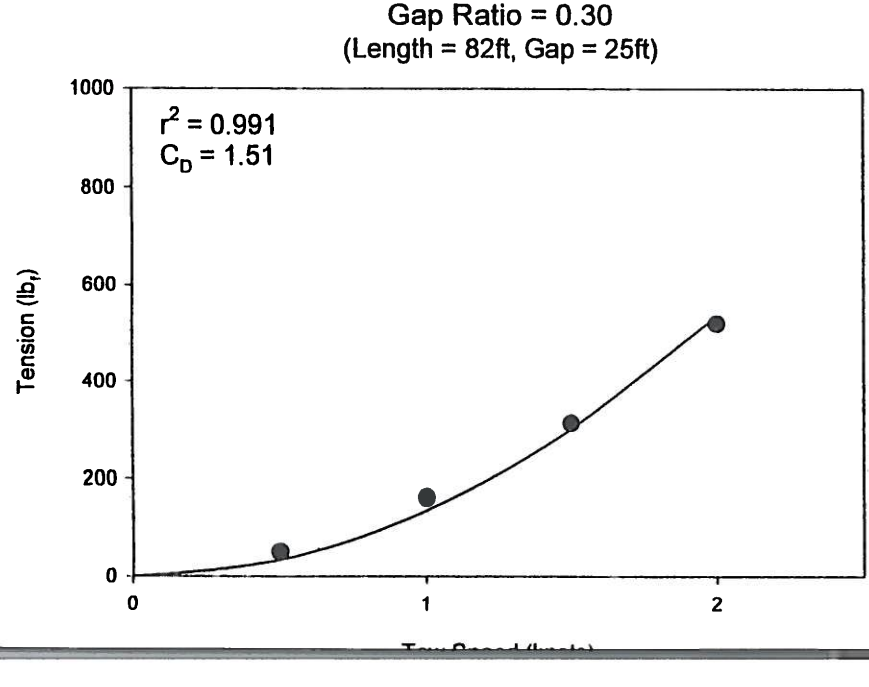


Figure C-6

USCG Oil-Stop Inflatable
Tow Speed vs Tension - Calm Conditions







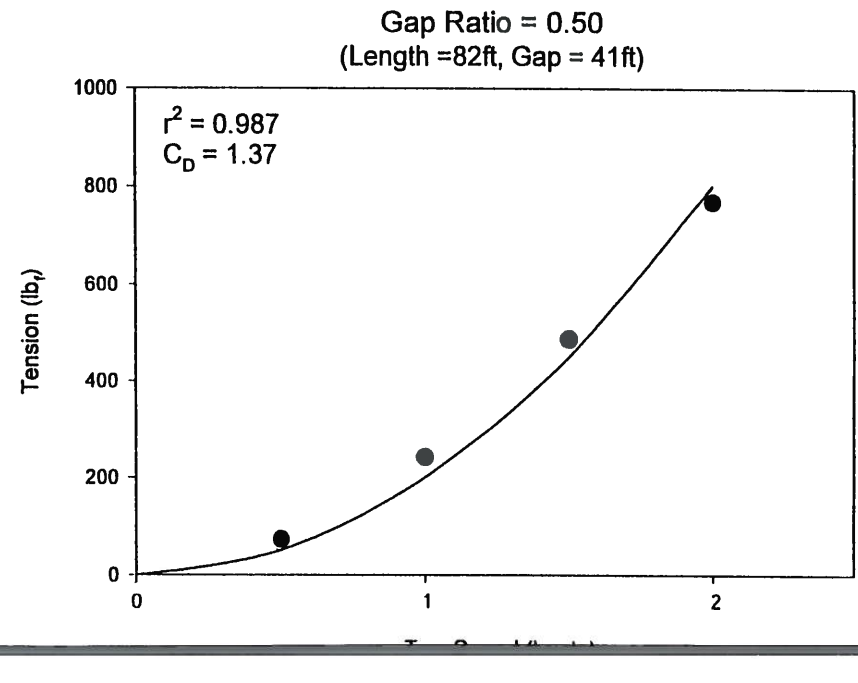
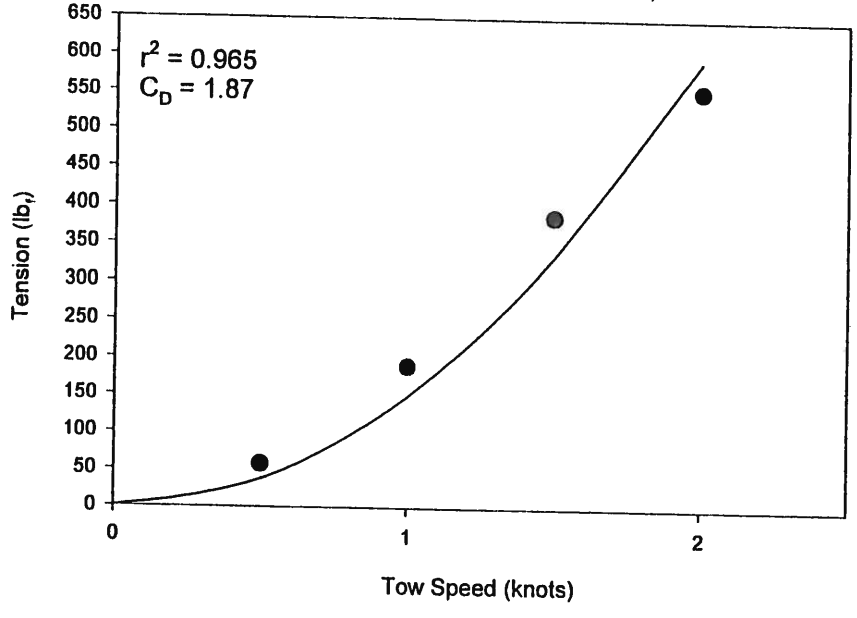


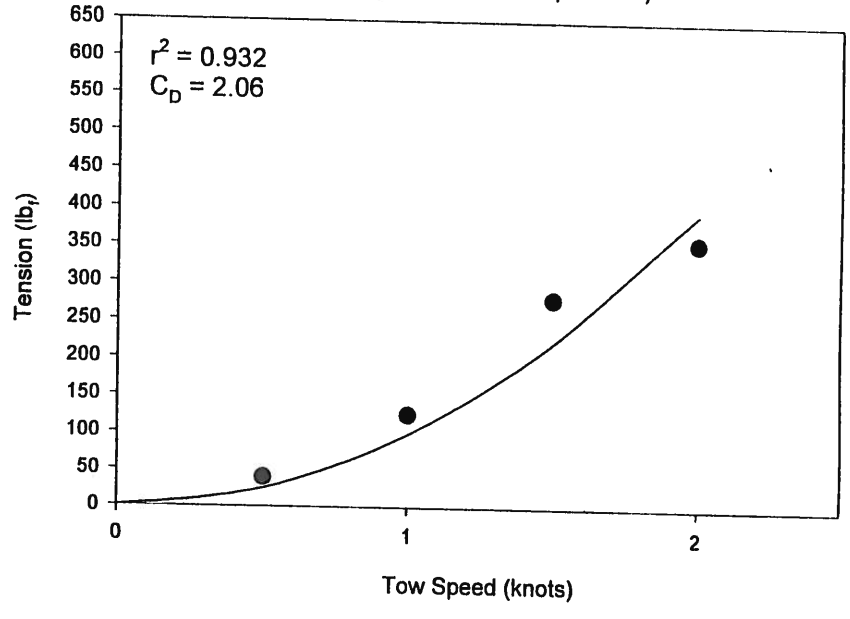
Figure C-7

CCG 18" Sanivan Curtain
Tow Speed vs Tension - Regular Wave Conditions

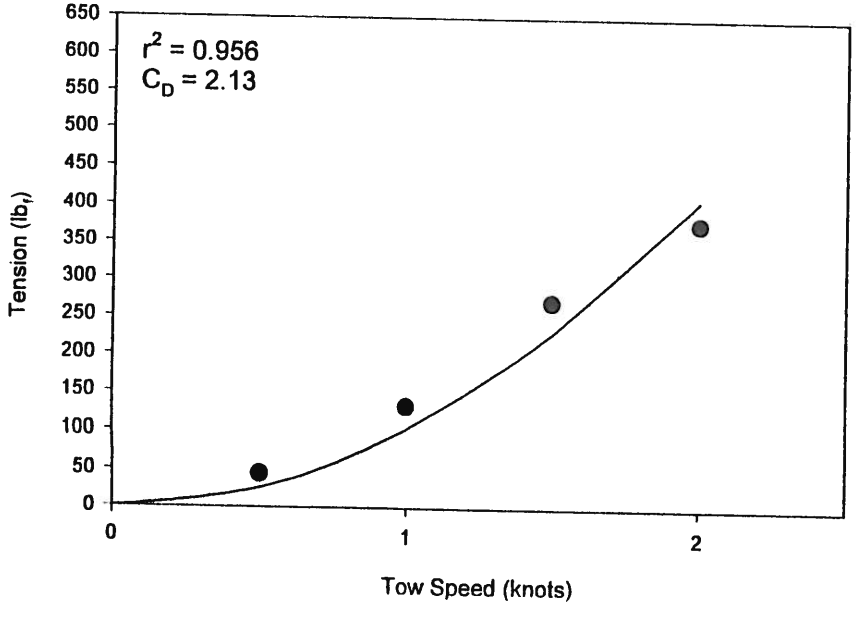
Gap Ratio = 0.33
(Length = 149.7ft, Gap = 50ft)



Gap Ratio = 0.20
(Length = 149.7ft, Gap = 30ft)



Gap Ratio = 0.30
(Length = 99.8ft, Gap = 30ft)



Gap Ratio = 0.50
(Length = 99.8ft, Gap = 50ft)

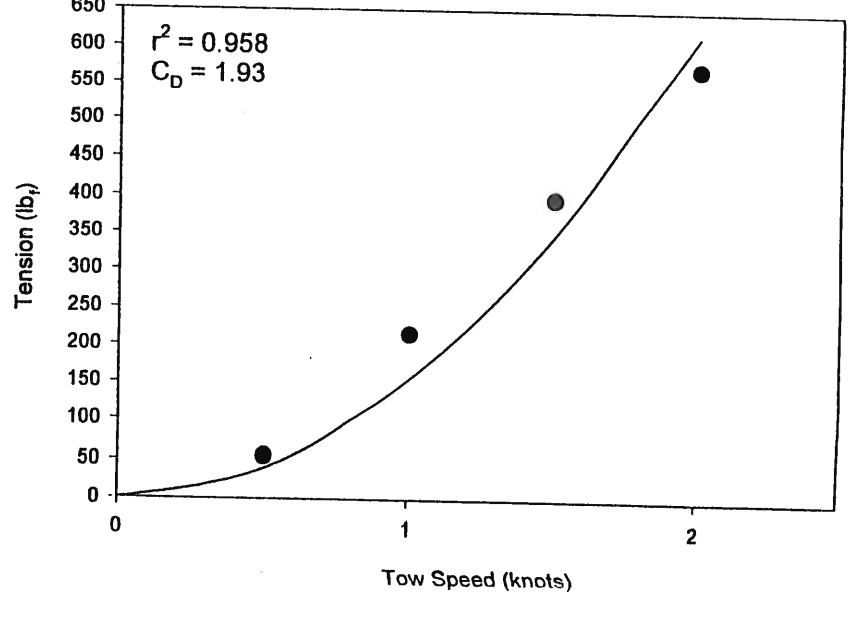
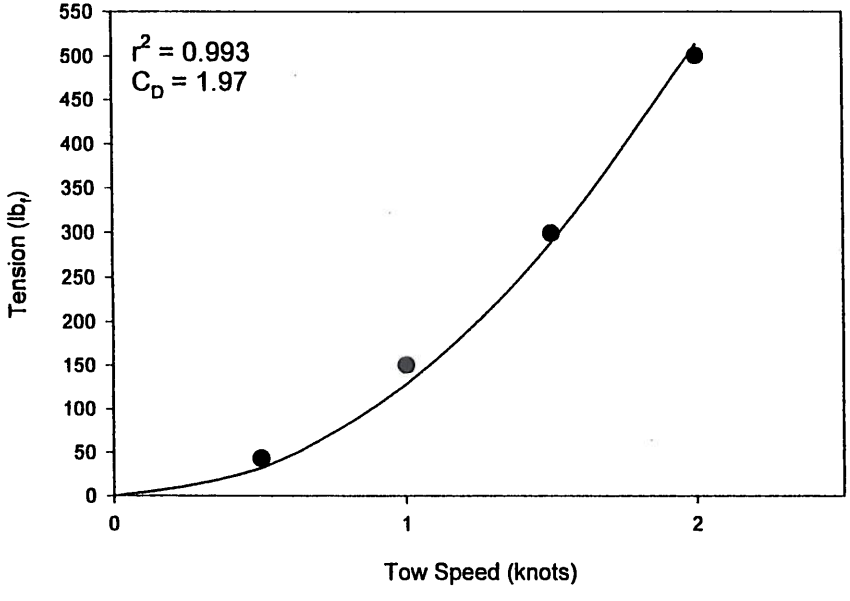


Figure C-8

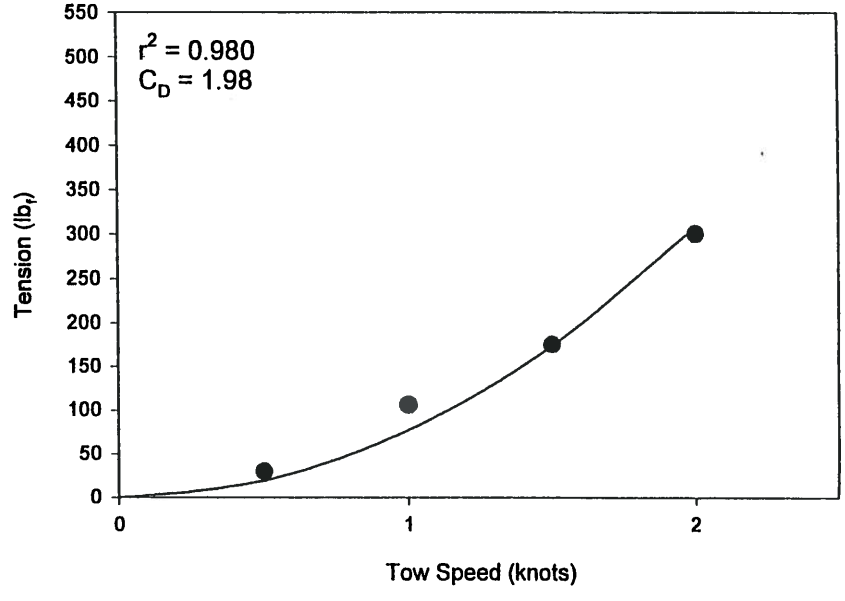
CCG 24" Sanivan Curtain

Tow Speed vs Tension - Regular Wave Conditions

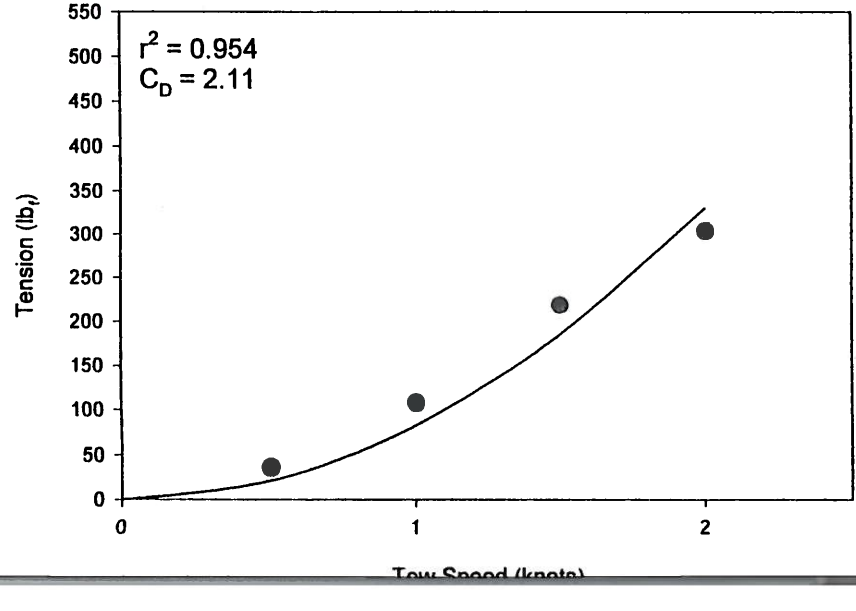
Gap Ratio = 0.33
(Length = 150ft, Gap = 50ft)



Gap Ratio = 0.20
(Length = 150ft, Gap = 30ft)



Gap Ratio = 0.30
(Length = 100ft, Gap = 30ft)



Gap Ratio = 0.50
(Length = 100ft, Gap = 50ft)

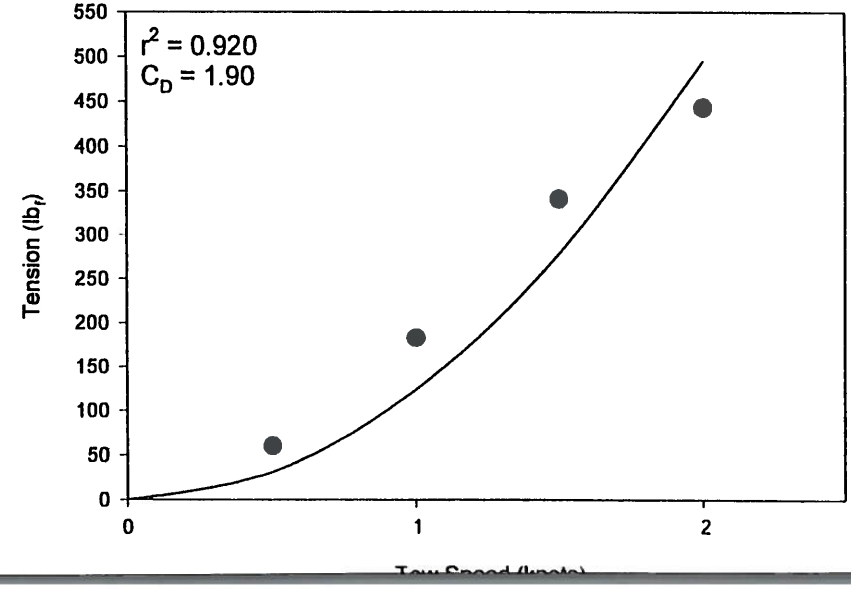
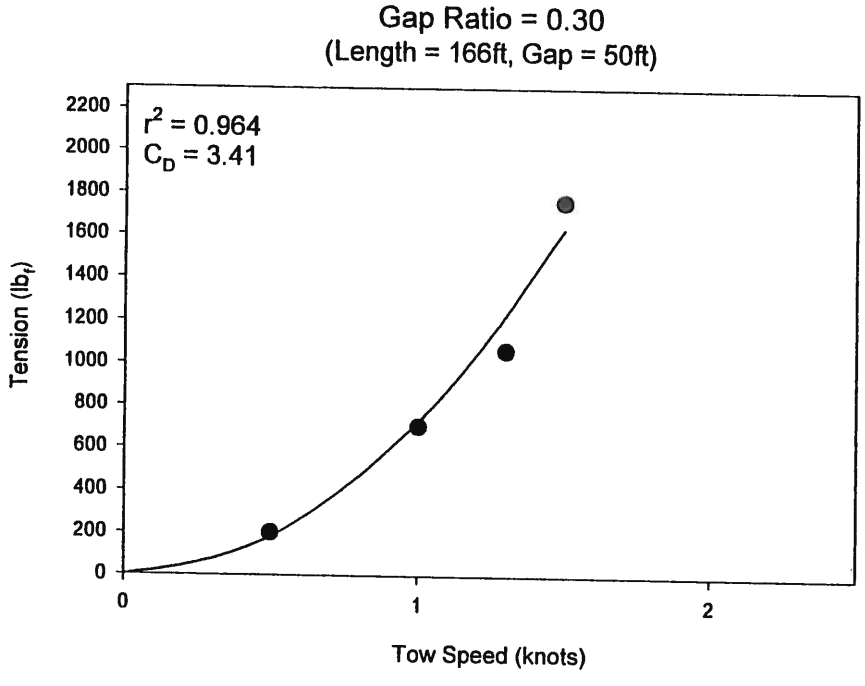
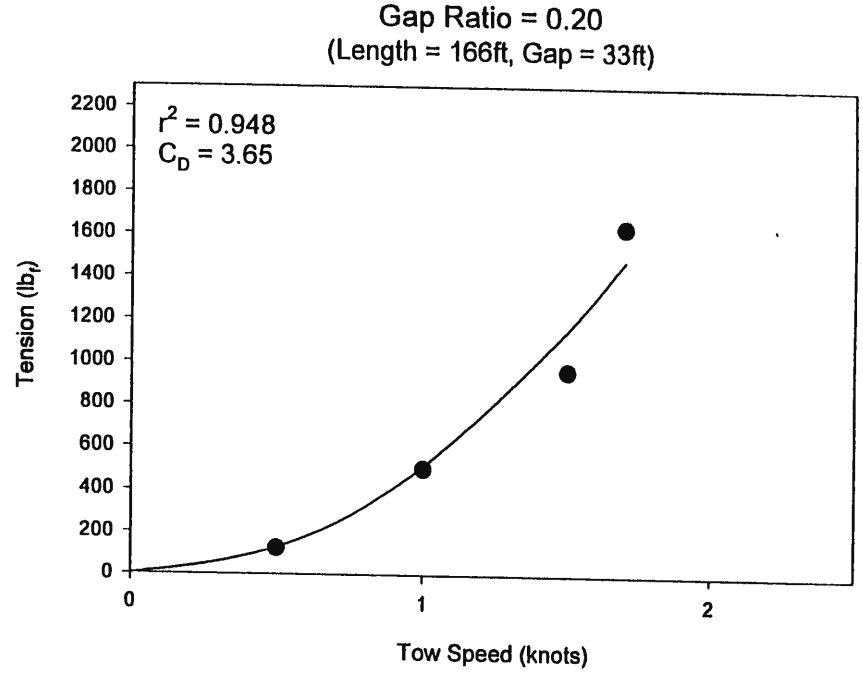
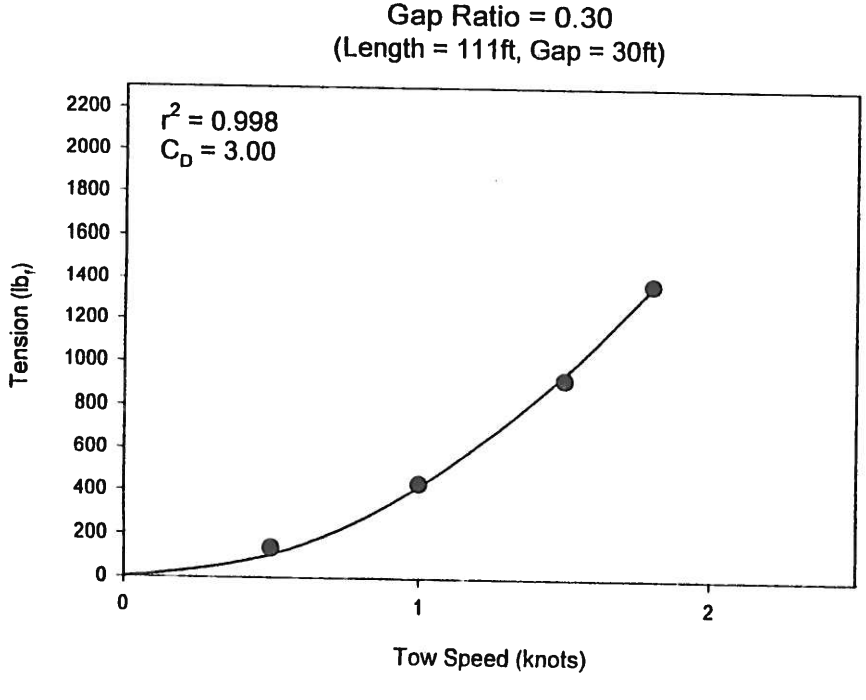


Figure C-9

US Navy USS-42 Inflatable
Tow Speed vs Tension - Regular Wave Conditions







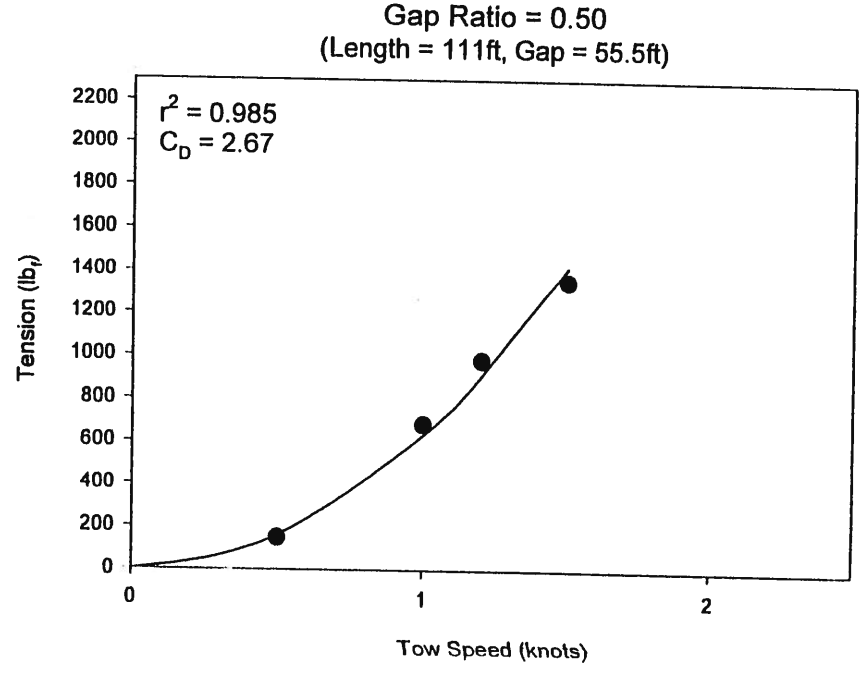
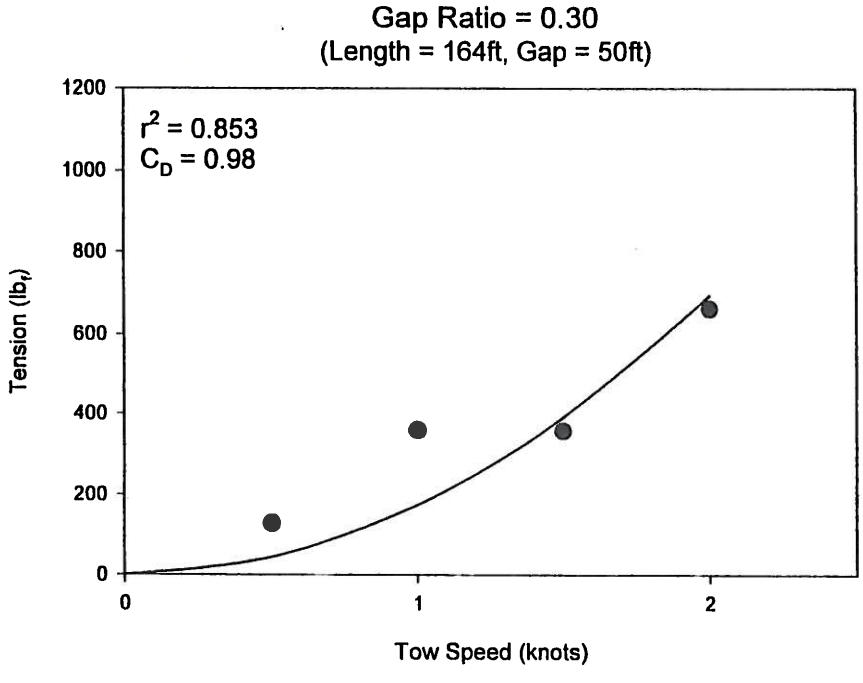
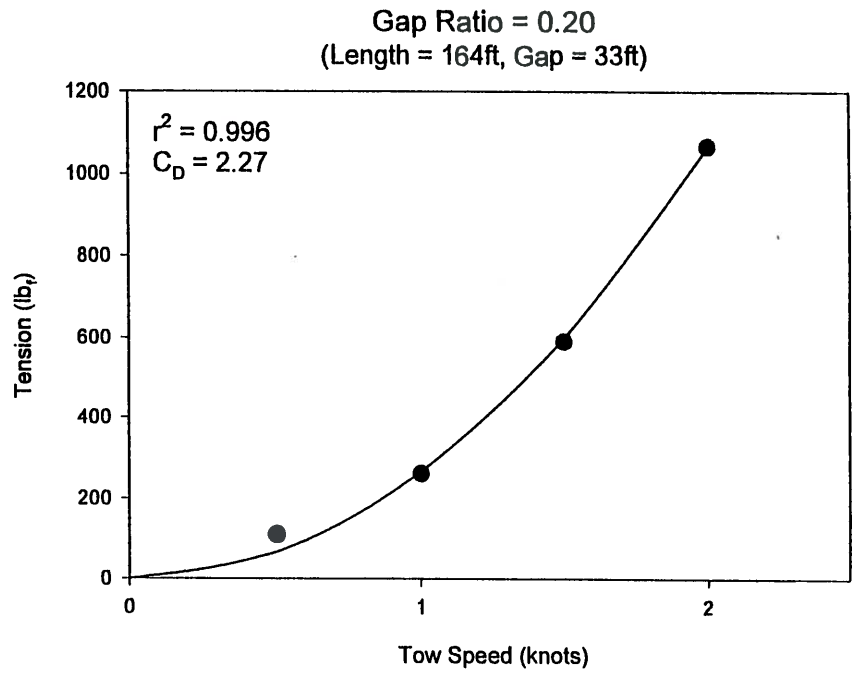


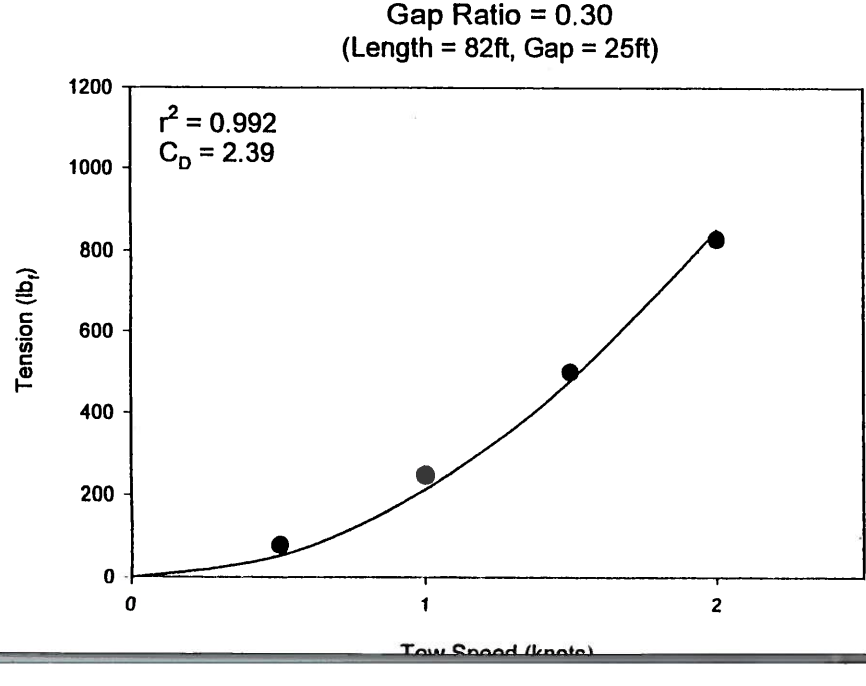
Figure C-10

USCG Oil-Stop Inflatable

Tow Speed vs Tension - Regular Wave Conditions







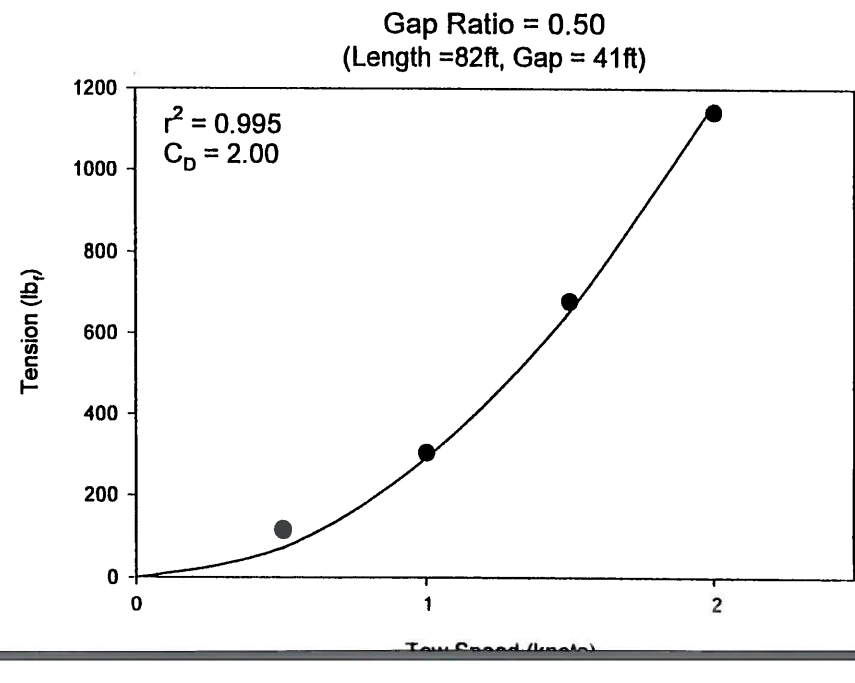
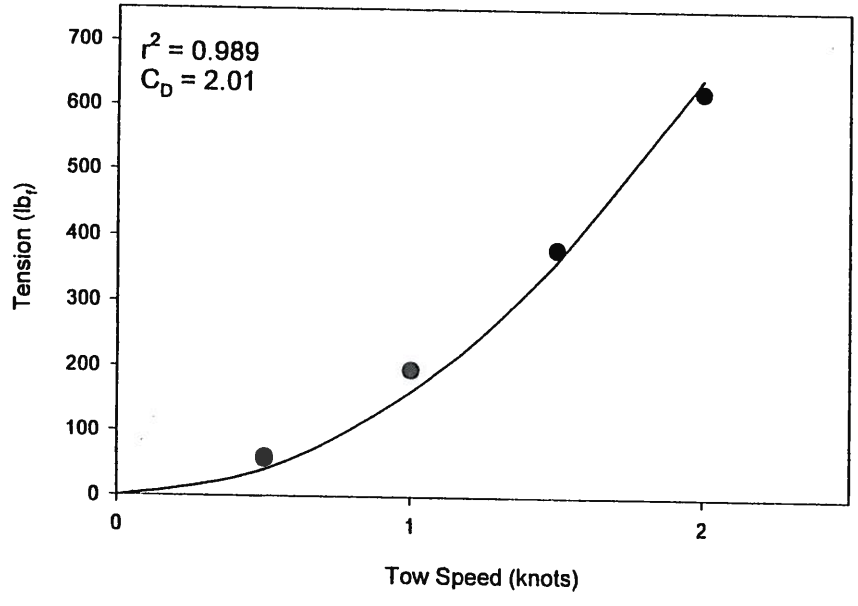


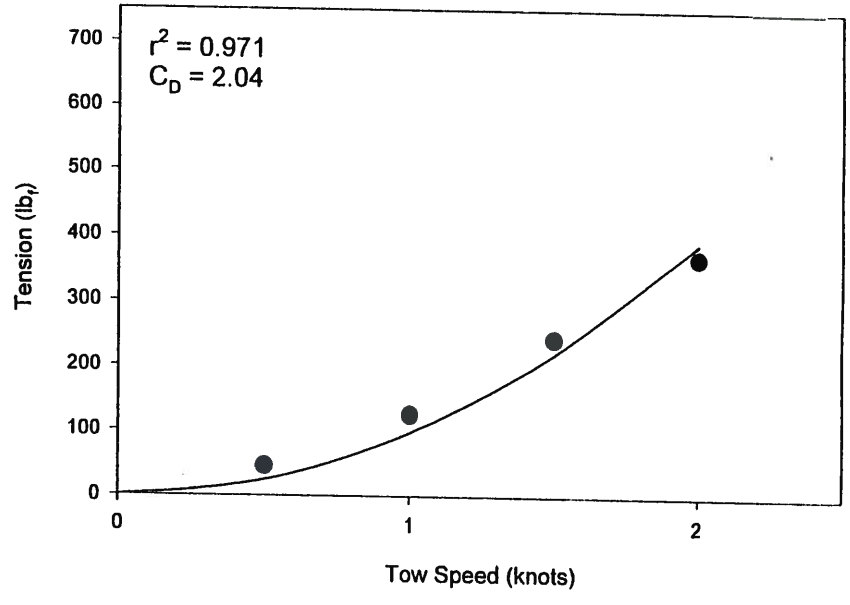
Figure C-11

CCG 18" Sanivan Curtain
Tow Speed vs Tension - Harbour Chop Wave Conditions

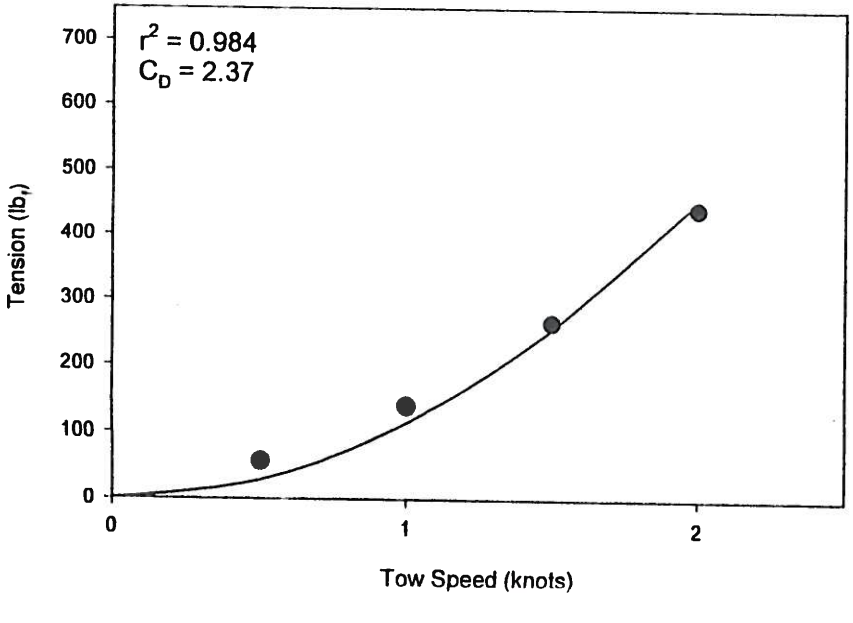
Gap Ratio = 0.33
(Length = 149.7ft, Gap = 50ft)



Gap Ratio = 0.20
(Length = 149.7ft, Gap = 30ft)



Gap Ratio = 0.30
(Length = 99.8ft, Gap = 30ft)



Gap Ratio = 0.50
(Length = 99.8ft, Gap = 50ft)

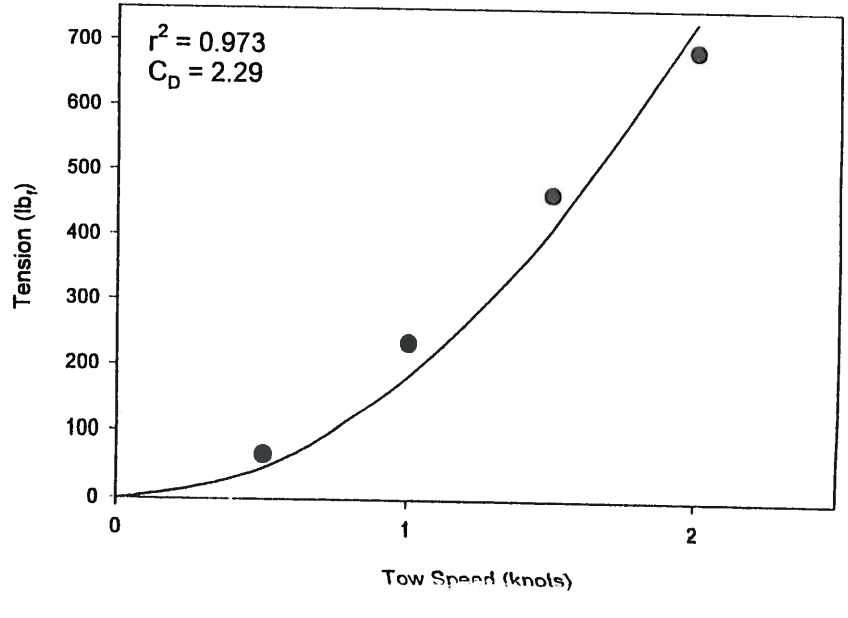
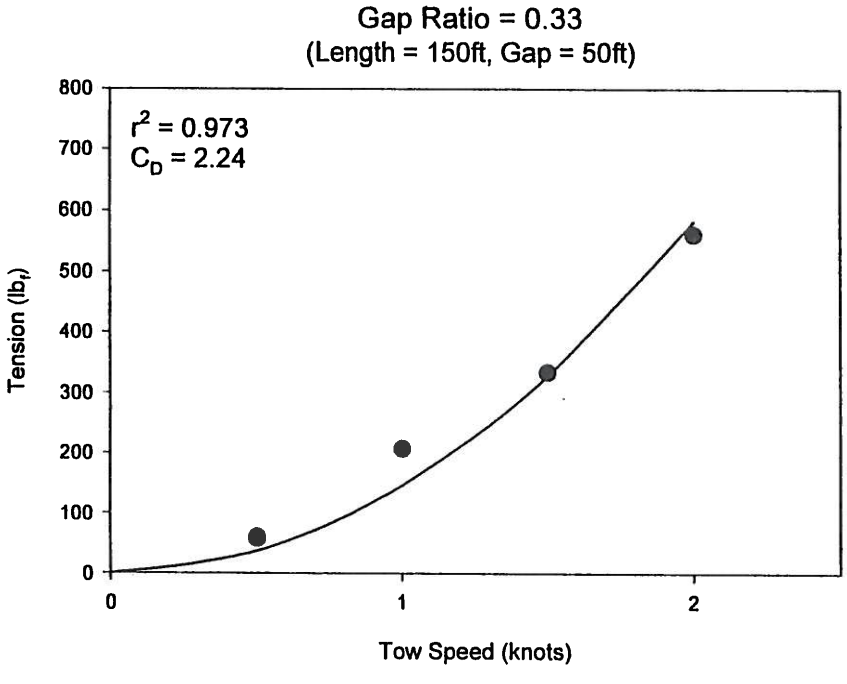
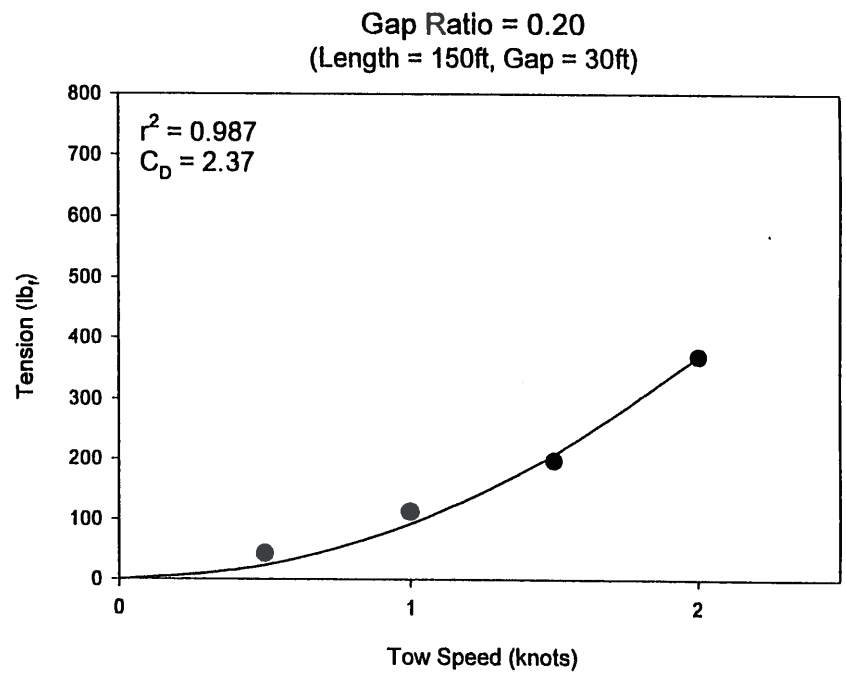


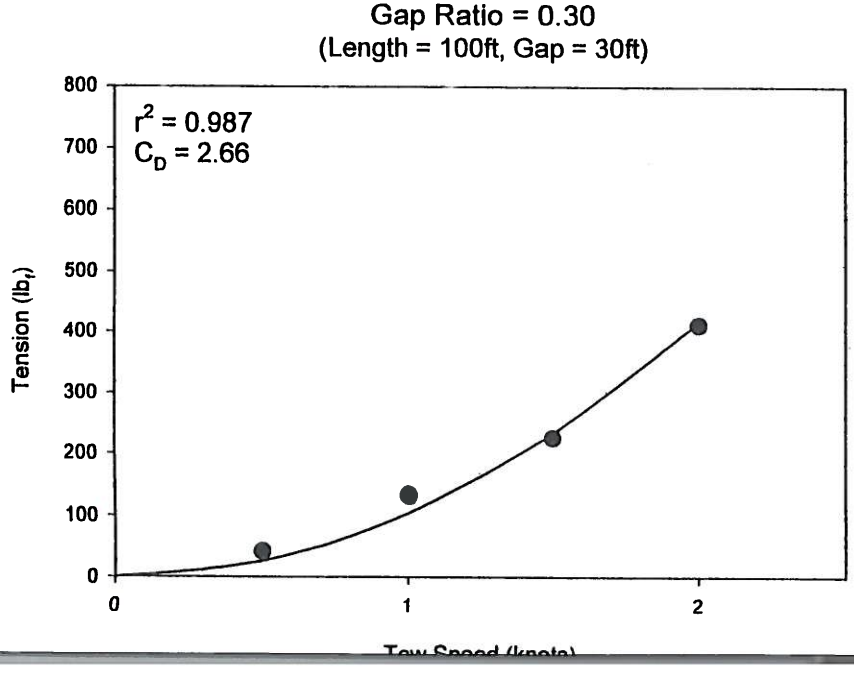
Figure C-12

CCG 24" Sanivan Curtain

Tow Speed vs Tension - Harbour Chop Wave Conditions







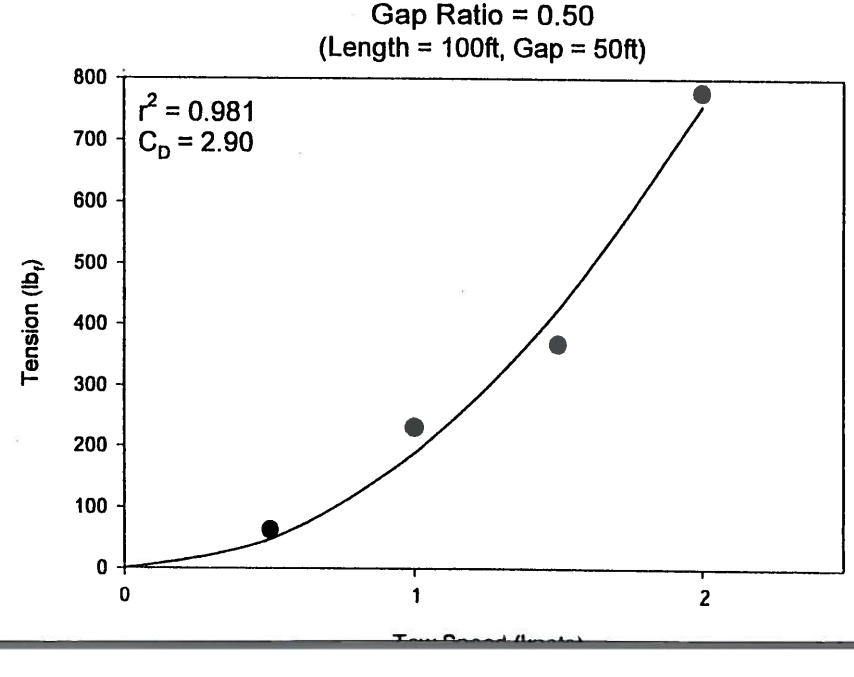
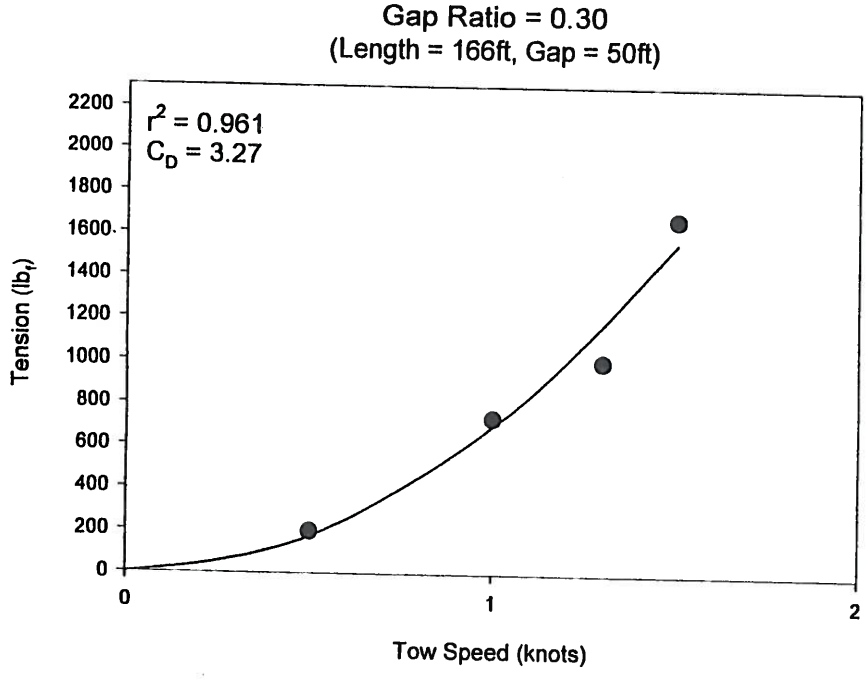
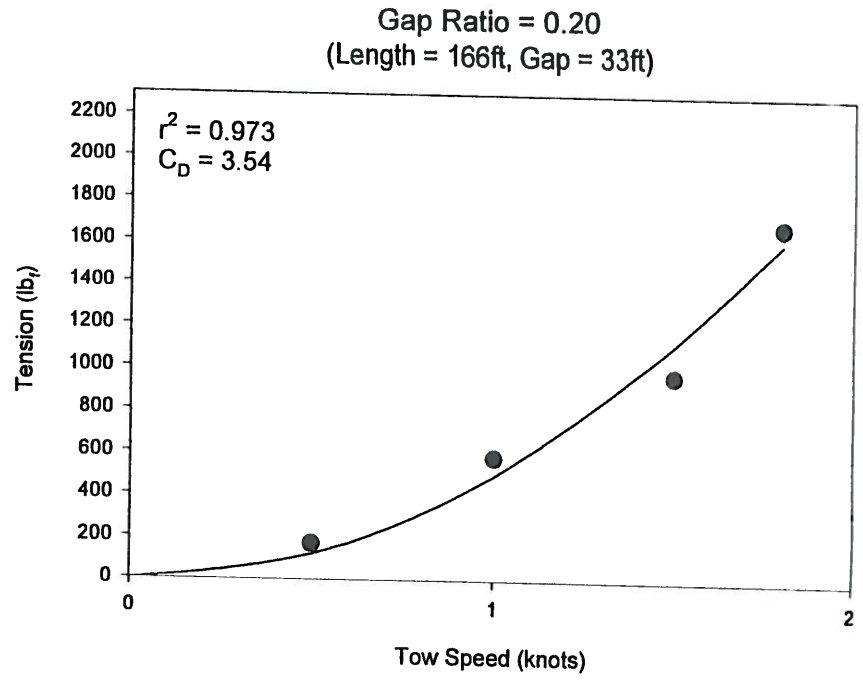
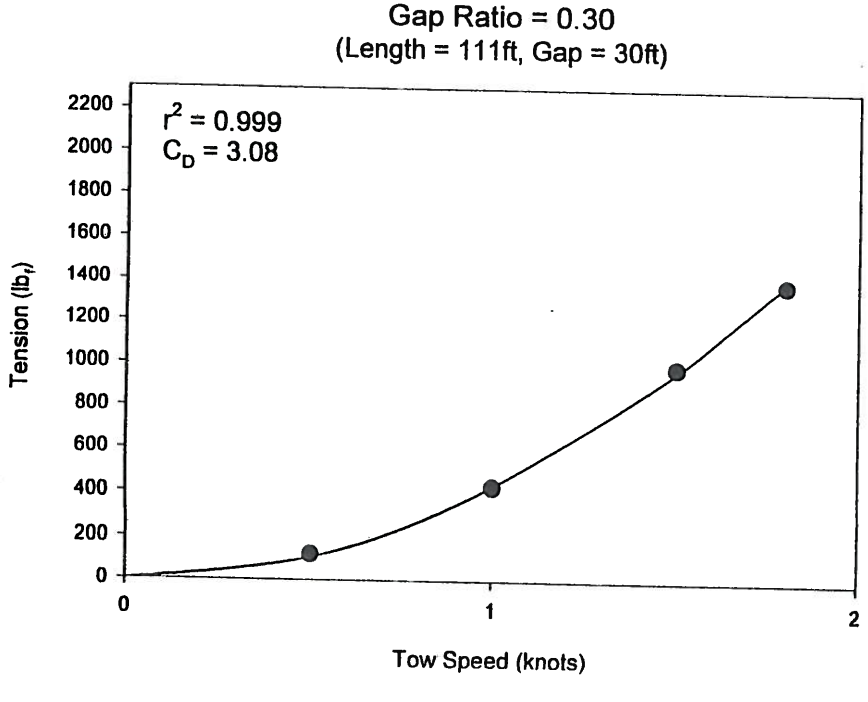


Figure C-13

US Navy USS-42 Inflatable
Tow Speed vs Tension - Harbour Chop Wave Conditions







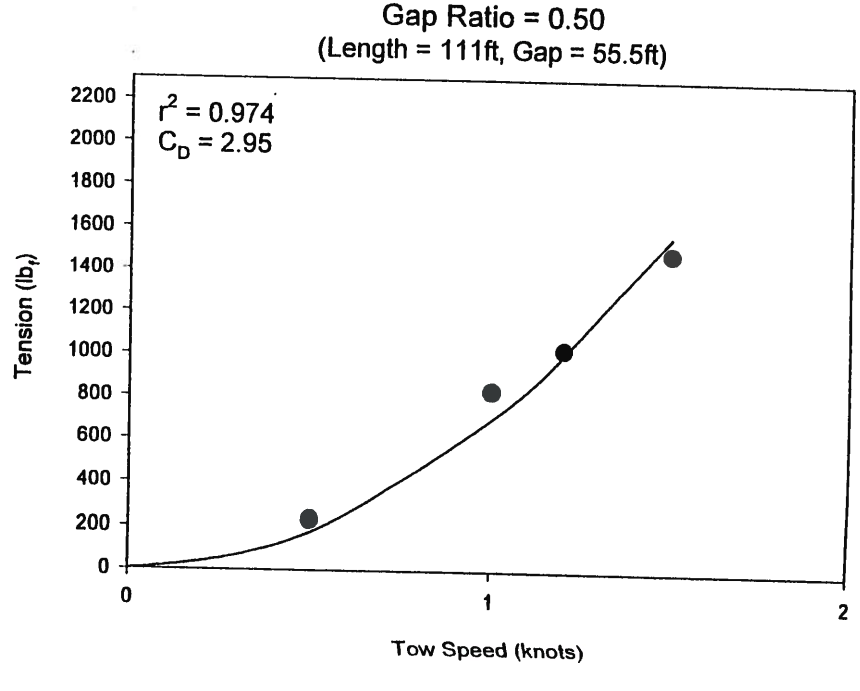
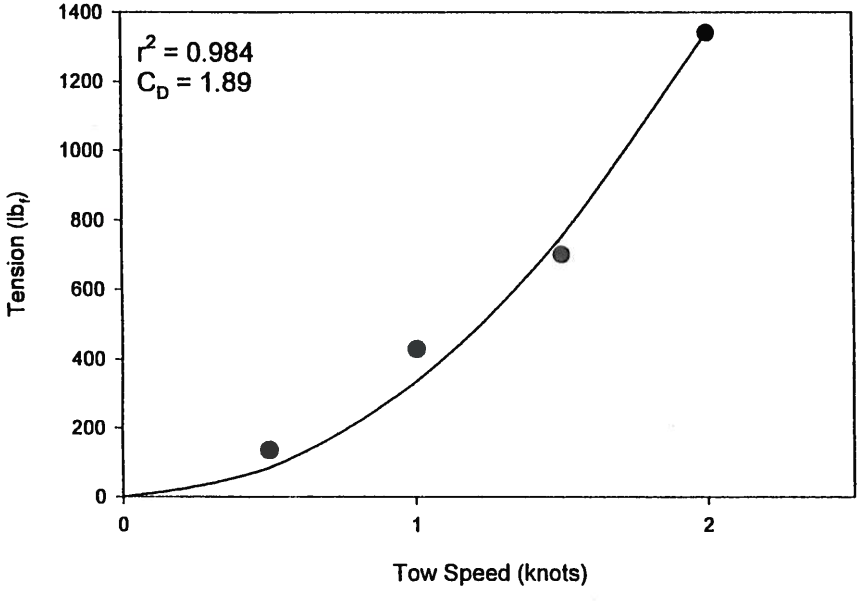


Figure C-14

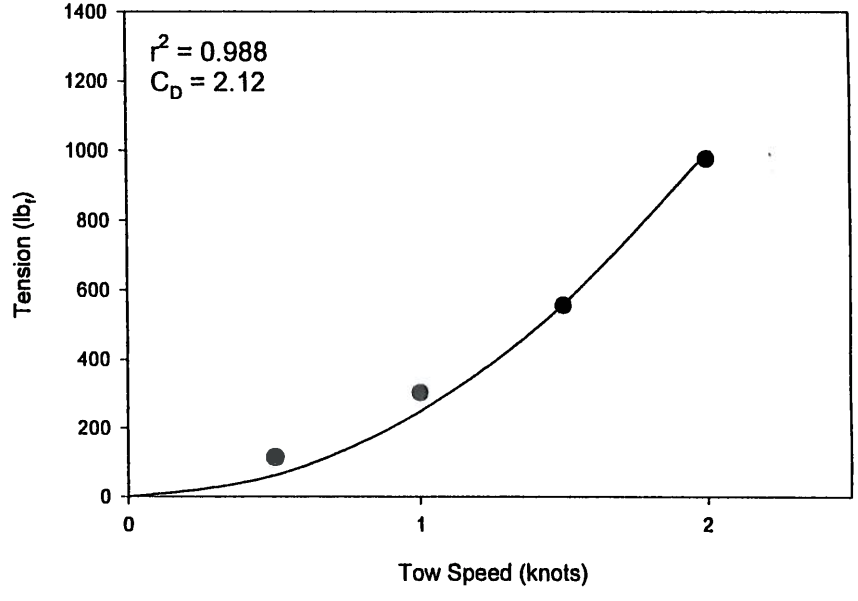
USCG Oil-Stop Inflatable

Tow Speed vs Tension - Harbour Chop Wave Conditions

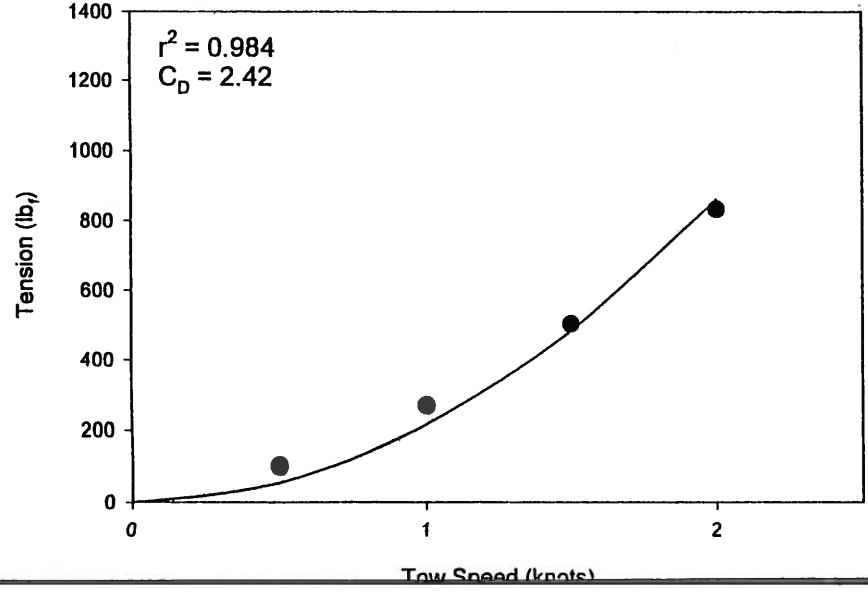
Gap Ratio = 0.30
(Length = 164ft, Gap = 50ft)



Gap Ratio = 0.20
(Length = 164ft, Gap = 33ft)



Gap Ratio = 0.30
(Length = 82ft, Gap = 25ft)



Gap Ratio = 0.50
(Length =82ft, Gap = 41ft)